Saimaa University of Applied Sciences
Technology Imatra
Degree Programme in Chemical Engineering

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LONGITUDINAL GRINDING OF NORWAY SPRUCE

Bachelor's Thesis 2011

ABSTRACT

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Saimaa University of Applied Sciences, Imatra.
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The purpose of this bachelor’s thesis was to analyze the paper properties of Norway spruce (softwood) pulp which was made in two grinding ways and different longitudinal grinding angle for the paper making process. In the theoretical part, the fundamentals of mechanical pulping and the properties of Norway Spruce was introduced by Saimaa University of Applied Sciences, Imatra.

In the experimental part, the Norway spruce pulps which were made by traditional grinding and longitudinal grinding were studied. These pulps were obtained from cutting the fresh Norway spruce wood at a different angle by mechanical pulping. Screened pulps were ground in angle 0°, 15°, 30°, 45° and angle 0° of reference type.

As a result, the grinding angle affected the properties of pulp and paper. For measuring the properties of the pulp, the bigger the grinding angle, the shorter the fiber length and less coarseness, the smaller the CSF freeness number, the bigger the water retention value. And for measuring the handmade paper, the paper which was made from a big grinding angle pulp had a smaller bulk, a higher tensile strength and burst strength, a lower tear strength, a worse air permeability and a better brightness.

Keywords: Norway Spruce, Softwood, Traditional Grinding, Longitudinal Grinding, Mechanical Pulping, Freeness, Strength.

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1 INTRODUCTION

In the final thesis, comparisons of the strength properties of paper and pulp made from Norway spruce (Picea abies) with traditional grinding process and longitudinal grinding process are the main purpose of this thesis. The pulps were ground to different degrees, the effects of the different ways of grinding and different longitudinal grinding degrees on the paper and pulp properties were compared.

In the theoretical part, the properties of Norway spruce were introduced, the structure of wood and the chemical composition of Norway spruce were explained. Mechanical pulping is introduced, the fundamentals of mechanism in refining process, beating process and fibrillation and the effects on fibers and pulps were also included. At last, in grinding part, different wood grinding processes and different grinders were described.

In the experimental part, pulp freeness (CSF) measurement, water retention, fiber length and coarseness, strength properties and brightness were tested in the laboratory of Saimaa University of Applied Sciences laboratory in Imatra.

2 MECHANICAL PULPING

Mechanical pulping is for breaking down the wood into fibers which uses mechanical methods. And mechanical pulps are made by mechanical defibration of wood that is carried out in two ways (grinding and refining process). Mechanical pulping is a thermomechanical process, but chemi-mechanical processes may also play a certain role. The traditional mechanical pulping includes grinding the logs against a revolving stone which uses abrasive action to grind the logs into pulp. Then, hot water is sprayed onto the stone to remove fibers from the pulp stone and to prevent fiber damage by friction-generated heat. Mechanical Pulping produces a high pulp yield of 85-95% compared to only 45% from Chemical Pulping. The process uses very little or no chemicals but is extremely energy intensive. Whilst this represents a source for the economic potential of mechanical pulps, the higher yield results in certain unfavorable properties compared to chemical pulp. (Mechanical Pulping 2006.)

2.1 General

The main mechanical pulping process are Stone Groundwood (SGW), Pressure Groundwood (PGW), Super Pressure Groundwood (PGW-S) and Thermo Groundwood (TGW), and the main mechanical pulps are Refiner Mechanical Pulp (PRMP), Thermomechanical pulp (TMP), Chemimechanical Pulp (CMP) and Chemithermomechanical Pulp (CTMP) (Paper Engineers` Association 2009, page 20). The aim of mechanical pulping is to produce fiber material with ideal properties which is in a form suitable for a specific papermaking process. e.g. the manufacture of printing papers and paper board. It can increase the proportion of mechanical pulps in printing papers, reduce wood consumption and environmental load and increase energy consumption.

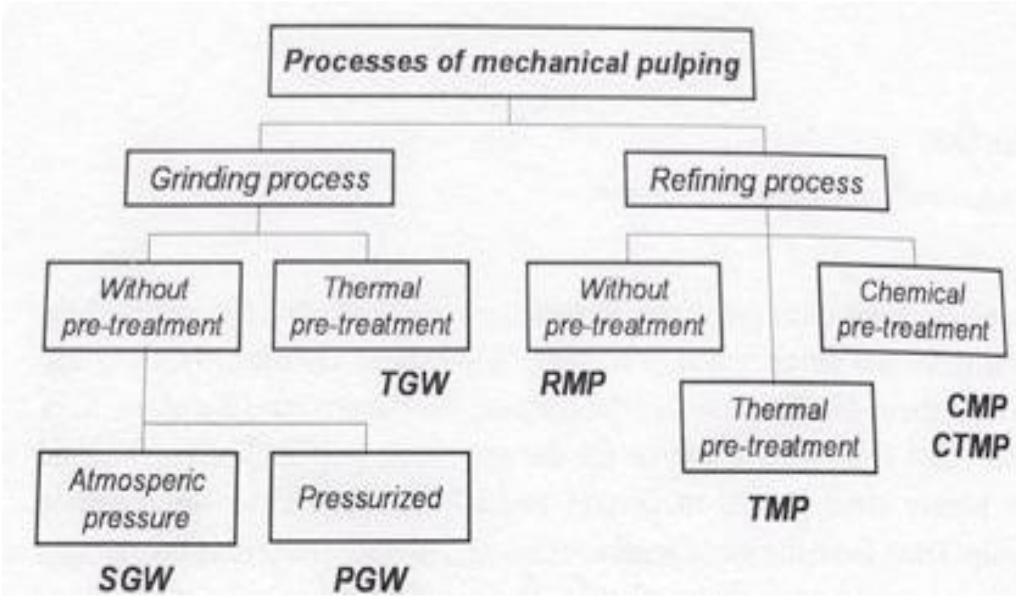


Fig.1: An overview of the basic mechanical pulping procedures (Sixta 2006, page 1072)

In Fig.1 above can be seen the two main processes used for the manufacturing of mechanical pulping. Grinding and refining have different treatment processes.

The most used wood for mechanical pulping is spruce, but today pine and hardwood are also increasing the interest. An ideal mechanical fiber pulp can produce a sheet of paper with high opacity, brightness, bulk and smoothness, and a suitable pore structure at a low grammage. So mechanical pulps are mainly used to produce printing papers. And this is also an advantage which compared with chemical pulps that mechanical pulps can produce low weight paper but still sufficient opacity and bulk.

An ideal mechanical pulping process requires the following elements:

- All wood fibers must be separated.
- The initial wood fiber length must be retained.
- The fiber walls must be delaminated (internal fibrillation).
- The middle lamella, at least, should be peeled off to produce fines, and the primary fiber wall should be partly peeled off to expose the secondary fibre wall.

- The secondary fiber wall must be fibrillated (external fibrillation).

(Paper Engineers` Association 2009, Page 19.)

2.2 Fundamentals of Mechanical Pulping

In mechanical pulping, the wood fibers are separated from each other by mechanical energy of various magnitude and duration applied to the wood matrix causing the bonds between the fibres to break gradually and fibre bundles to produce a suitable papermaking pulp.

Grinding (see Chapter 3) and refining are the heart of the manufacturing of mechanical pulping. In the stone ground wood process (SGW) or in the pressurised ground wood process (PGW), logs are pressed against a rotating grinder stone with simultaneous addition of water. Refiner Mechanical Pulps (RMP, Thermo-Mechanical Pulps = TMP) are produced by defiberizing wood chips between disc refiners. The elements causing the mechanical action are grits on a pulp stone in the grinder and bar edges on a steel disc in the refiner, giving the resulting pulps a typical blend of fibers and fiber fragments. (Mechanical Pulping and Chemical Pulping.)

There are many different operating and design variables that affect the way the refiner applies forces to the wood raw material, such as the refining power, production rate, refining consistency, steam pressures, plate pattern and disc speed. In grinding, the fiber structure of the wood matrix is subjected to cyclical stress by a series of shear and compression forces. A condition that enables the fibers to deform by compression and shear force is the hollow structure of fibers. And the energy absorbed in grinding process can be seen like the curves of stress versus strain which is shown in figures 2, 3 and 4.

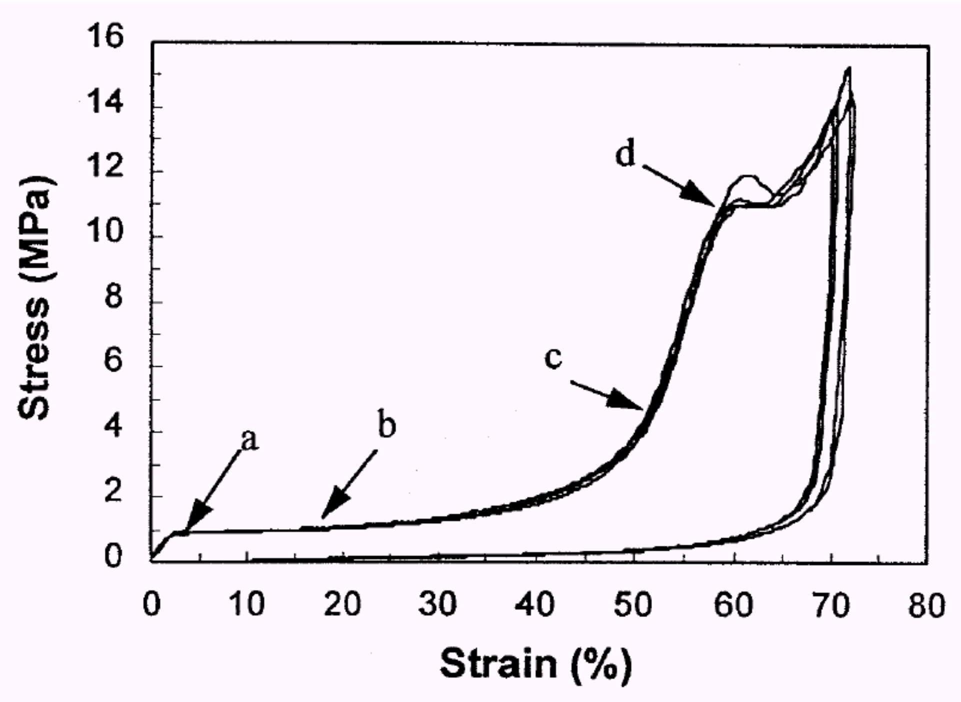


Fig.2: Stress versus strain curves for several specimens in a radial compression at 98°C (Paper Engineers` Association 2009, page 47)

In the figure 2, a is wet wood through the elastic, b is the plateau, c is the densification region of the earlywood fibers, d is the point where densification of the latewood fraction starts. It is showed that irreversible structural changes in wood can be achieved by means of radial compression of the wood beyond its elastic region to a plateau region where a preferably plastic strain takes part.

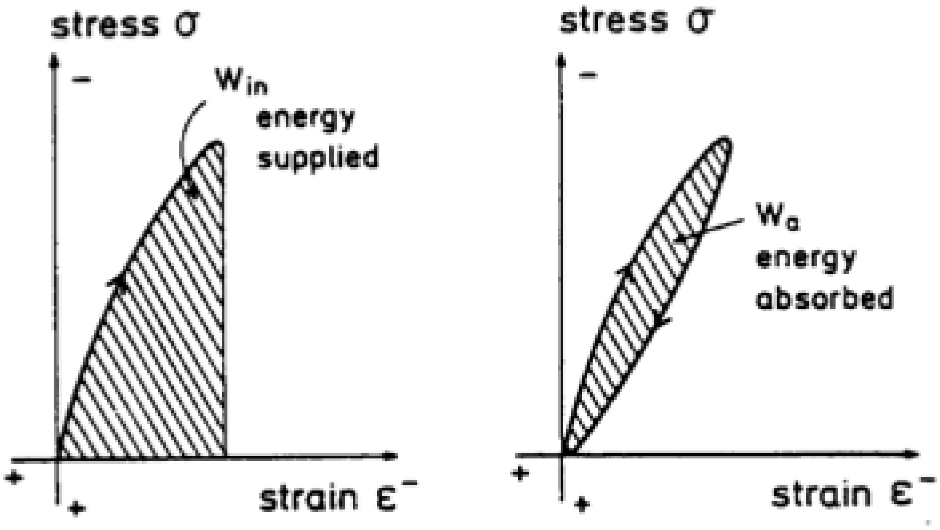


Fig.3: Energy absorption of mechanical pulping process (Paper Science & Technology)

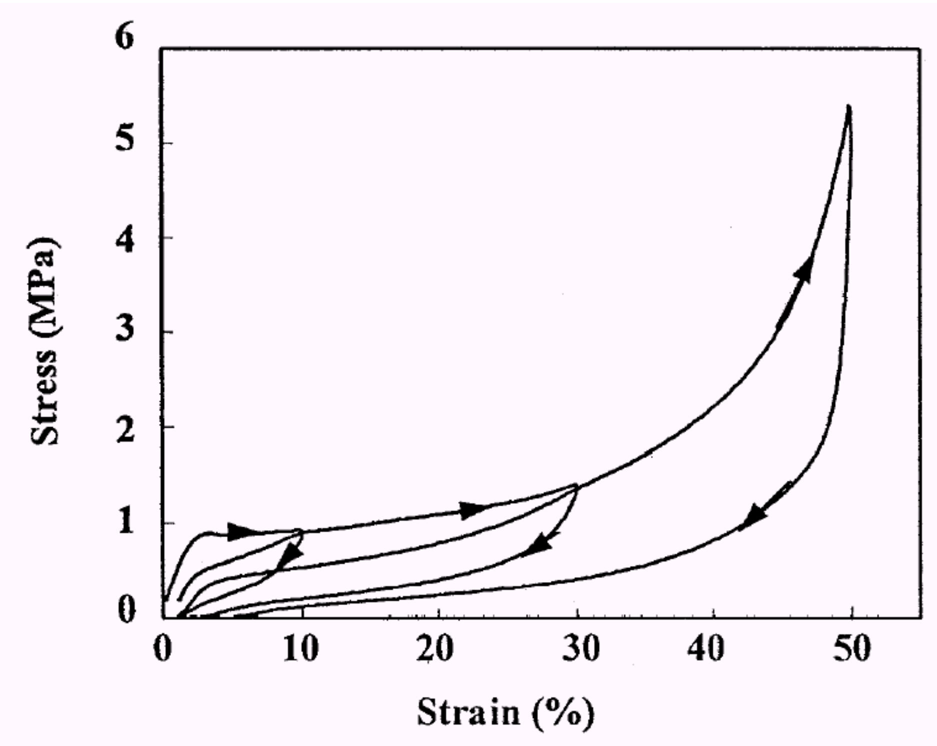


Fig.4: Stress versus strain for three consecutive compression cycles to 10, 30 and 50% strain at 98°C (Paper Engineers` Association 2009, page 47)

According to the figure 3, the wood fibers are separated from each other by mechanical energy applied to the wood matrix, the bonds between the fibers to break gradually and fiber bundles, single fibers and fiber fragments to be released. And in the figure 4, most of the energy is absorbed in irreversible plastic deformation and small part in reversible viscoelastic deformation.

The stress means the force used, the area of the stress-strain curve means the amount of absorbed energy. The curve represents the function of energy absorption in grinding. The more force is used, the more energy is absorbed. Most of the deformation takes place in the elastic region of the stress-strain curve with very little fatigue but to a large degree due to hysteresis loss. However, the probability of plastic deformation or fatigue of the fiber structure will increase because of the repeated compression and shear pulses. (Paper Engineers` Association 2009, page 48)

2.2.1 Fundamental Mechanisms in Refining

The refining is the main method for producing thermomechanical pulp. In refining, wood chips are fed between two parallel discs and at least one of those is rotating. The rotational energy is transferred into the pulp by compression and frictional forces so that chips are broken down and a wood material is developed suitable for papermaking due to compressive and shearing forces. The main mechanisms in refining are defibration and fibrillation. And they are determined by the flow conditions in the refiner and the rheological properties of the wood and fibers. (Illikainen 2008.)

2.2.1.1 Pulp flow behaviour

Flow phenomena, pulp properties, as well as energy consumption of refining vary significantly depending on the radial position in a refiner disc gap. (Huhtanen 2004). The disc gap is divided into three different zones, as seen in Fig. 5.

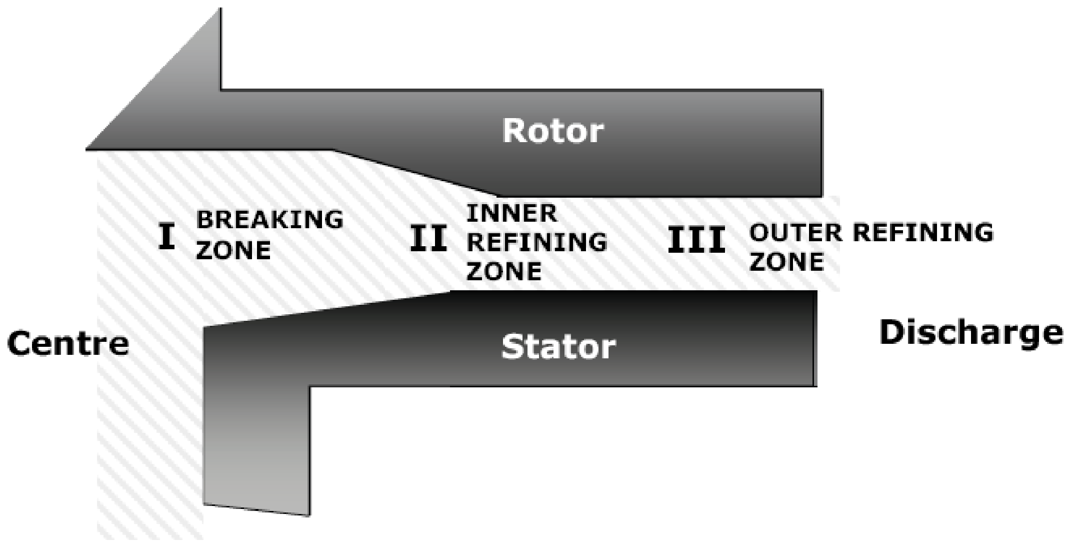


Fig.5: The composition of disc gap in refining (Illikainen 2008)

In Fig. 5, the inner most part of the refiner is breaking zone (Zone I), the middle part is inner refining zone (Zone II) and the narrow part is outer refining zone (Zone III).

In the breaking zone, wood chips are shredded into coarse pulp immediately, it shows that there is a considerable circulation of coarse pulp and shives. Backflow is in the grooves of the stationary plate and forward along grooves of the rotating plate. The transition area of the inner refining zone which is covered with pulp between coarse and fine pattern is even higher. However, the amount of pulp coverage is the lowest in the outer refining zone. (Atack et al. 1984.) In the outer refining zone, fiber flow is radiating outwards forming fiber flocs that move in tangent direction and change their shape and destruction. The fibres and fibre flocs have also been seen to be trapped on the bar edges where they are subjected to the refining action. (Stationwala 1992.)

2.2.1.2 Effects on fibers and pulp

Refining can change fiber structure by subjecting fibers to mechanical stress. It can be divided into primary and secondary changes. Removal of primary fiber wall, internal fibrillation, external fibrillation, shortening of fibers, creation of fines, delamination, swelling, straightening of fibers (Fig.6) are the main effects. For pulp, the refining will weaken pulp dewatering properties, increase dewatering resistance and pulp drainability will be reduced.

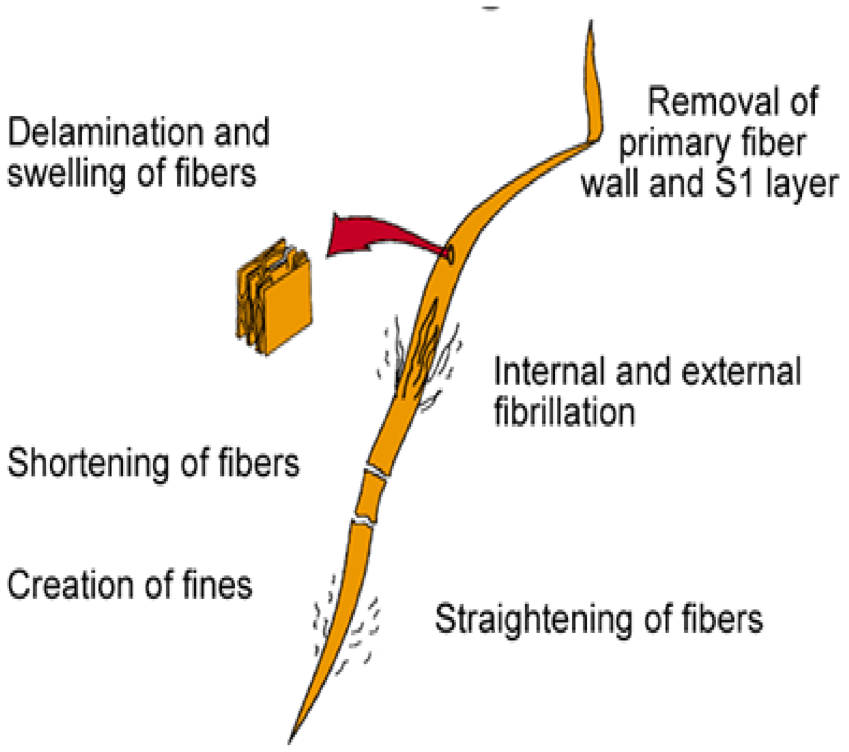
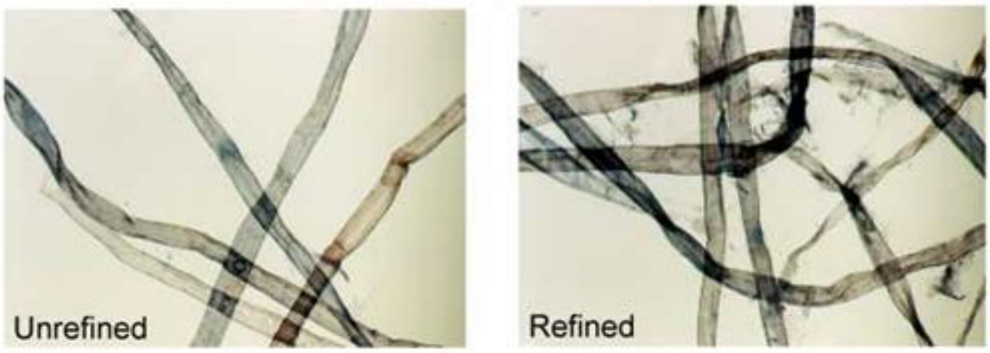


Fig.6: The effects of refining on fibers (Know pap 10.0)

Actually, the effects of refining on fibers can be explained as follows: 1) Fibers could be enlarged. 2) More fiber flexibility. 3) Fibrillation of the secondary wall. 4) Losing initial fiber walls in refining, create a better situation for flexibility and connection. 5) Slits in fibers and increase in fine particles with the objective of a desirable formation of paper sheets.(Mirshokraei 1995.)



	Unrefined	Refined (200 kWh/t)
• Freeness, ml	735	455
• Fiber length, mm	2.34	2.19
• Tensile index, Nm/g	28.4	73.8
• Tear index, mNm^2/g	20.5	16.0
• Air permeability, Bendtsen ml	1350	1040
• Bulk, cm^3/g	1.79	1.52

Fig.7: The effects of refining on pulp (Know pap 10.0)

In fact, refining influences all paper properties to some extent. Refining requires a considerable amount of energy to increase the drainage resistance of the refined pulp and decreases the bulk of the paper. The refining should not be brought further in commercial operation than is absolutely necessary for satisfying the paper quality specifications as both positive and negative effects. (Gellerstedt et al. 2009, page 121)

2.2.2 Fibrillation

Fibrillation is the rapid, irregular, and unsynchronized contraction of fibers. It includes internal and external fibrillation. The partial delamination of the cell wall, resulting in a microscopically hairy appearance of the wetted fiber surfaces. The "hairs" are also called fibrillation. (Fig.8)

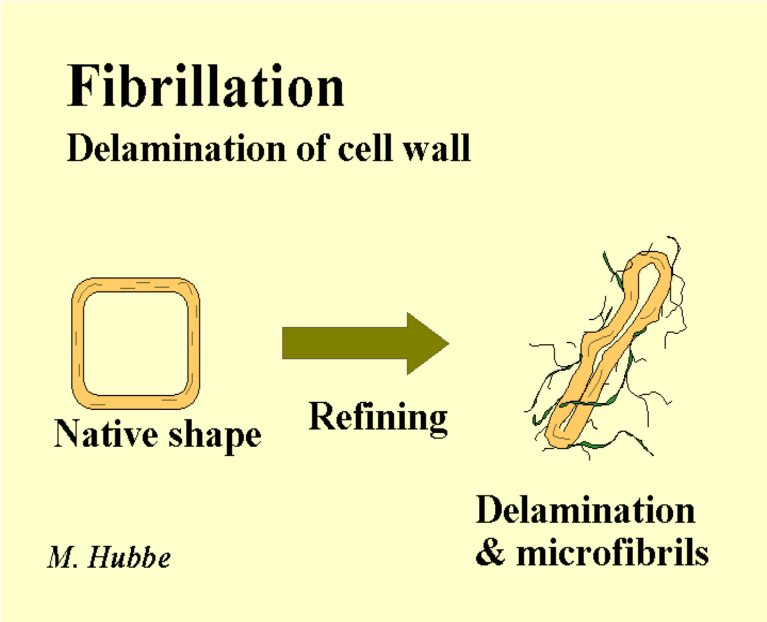


Fig.8: The process of fibrillation (Hubbe)

2.2.2.1 External Fibrillation

External fibrillation can be defined as the partial removal of the fibre wall, leaving it still attached to the fibre. The fiber surface may come in contact with external fiber layer particles after removal of the primary fiber wall and S1 layer. And a fibrillated surface structure is created if they happen to stick to the fiber surface. S2 layer micro-fibrils are almost entirely in the fiber axle direction leading to a very strong external fibrillation. However, the actual external fibrillation will start only after emergence of the fiber layer S2. Due to external fibrillation, the external fiber surface becomes larger which is good for inter-fiber bond creation. (Clark 1985, page 162)

2.2.2.2 Internal Fibrillation

Fibre swelling is often called internal fibrillation. The internal fiber structure becomes more detached which leads to fiber swelling after refining breaks the hydrogen bonds between internal fiber layers. Chemical pulp fibers become more flexible and plastic due to internal fibrillation. At the sheet formation stage, fibers treated like this are well bonded to each other and inter-fiber surfaces become larger and conditions are favorable for inter-fiber bonds creation. (Clark 1985, page 165)

Due to internal fibrillation, fiber becomes more flexible and plastic and begins to swell, which is conducive to the formation of contacts with other fibers. External fibrillation and dissolution of fiber component substances will create opportunities for building up the strong fiber bonds at the fiber contact points.

2.2.2 Beating

Beating is the most important mechanical treatment carried out on pulp with the aim to achieve pulp properties suitable for papermaking. The term beating is used mainly for treatments in laboratory equipment and in old-fashioned mill beaters. It highly affects the physical properties of the prepared paper sheets. It serves the purpose of increasing the area of contact between the fibers by increasing their surface through fibrilation and by making them more flexible. (Raymond 1986.) A JOKRO mill, a PFI mill or a small refiner can be used for the beating of small quantities of pulp (Sixta 2006, page1281).

Beating increases fibre flexibility and collapse. Fibres are straightened typically during low-consistency beating. Beating increases the volume of so-called macropores in the fibre cell wall. Macropores are created originally when lignin is removed from the cell wall in pulp cooking. Beating of dried chemical pulp reopens most macropores during pulp drying. Most paper strength properties are also improved by beating which increases the bonding ability of fibres. (Hiltunen 2003.) Fibre shortening occurs with high intensity beating and at high beating energy levels in low-intensity beating. Internal fibrillation is often considered as the most important beating effect. As beating gives a clearly higher elastic modulus at the same density compared to wet pressing, external fibrillation has only a limited effect on the tensile strength or elastic modulus. (Hartman 1985.)

3 GRINDING

The grinding process is one of the oldest wood processing techniques. The first commercial wood grinder was introduced in Germany in 1855. Grinding is a mechanical stock preparation method, for producing groundwood. At mechanical stock preparation, the fibers in the wood are separated from each other by means of mechanical strain. Part of the mechanical energy converts through friction to heat, which participates in softening the lignin binding the wood fibers together and assists in opening the bond between the fibers. The finished groundwood contains the wood components (cellulose, hemicellulose, and lignin) in nearly original proportions, whereby the same amount of wood yields almost twice the amount of stock as compared to the cellulose process, respectively. The yield of the grinding process is 96 to 98%. However, considering losses at debarking, etc., the yield remains at some 92 to 95%. (Fagerhed & Lönnberg 1988.)

3.1 Introduction

In grinding, the wood logs are pressed sideways against a rotating grindstone together with a large amount of water, which acts both as a cooling and a lubricating medium so that the wood fibers are perpendicular to the motion of the pulpstone surface. The surface of the stone is a hard and porous ceramic composite. The logs with a typical length of 1-1.5m are loaded in a grinder magazine parallel with the stone shaft and fed against the stone with a typical speed of 1-2mm/s. Then, the wood fibers are separated by the rotating stone transfering through grit particles and energy to the wood. (Paper Engineers` Association 2009, page 40.)

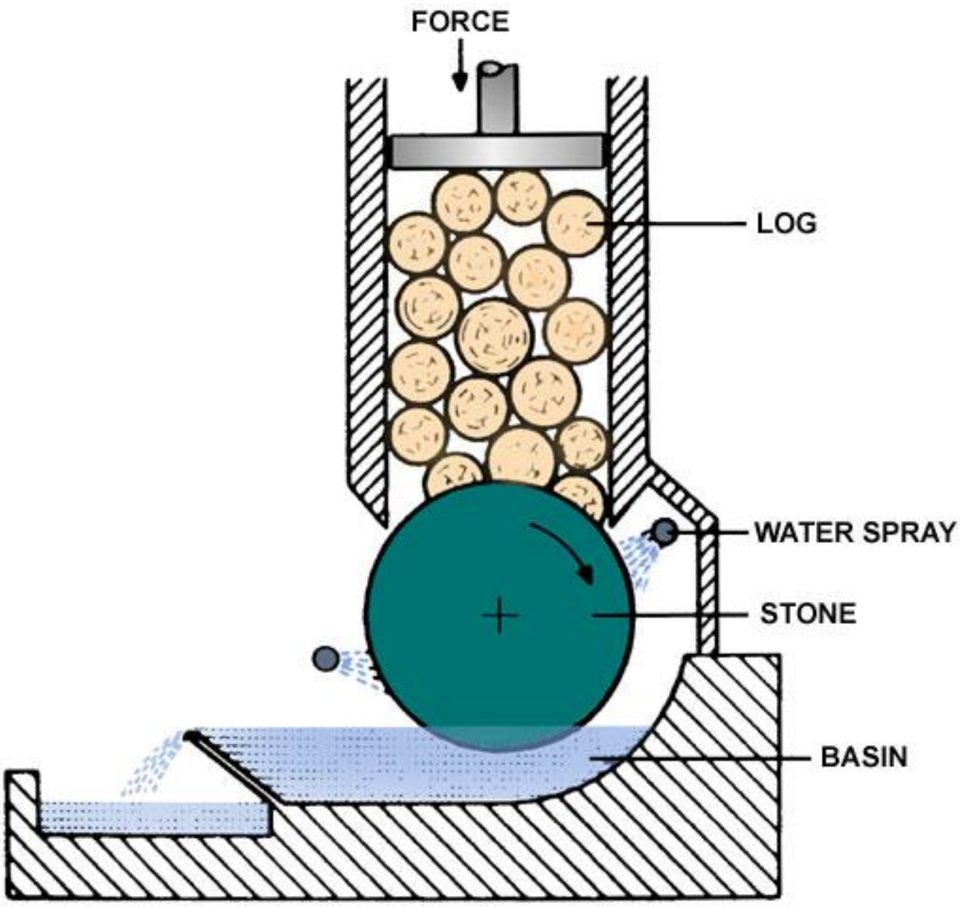


Fig.9: Grinding principle (Know pap 10.0)

The figure 9 above shows the principle of grinding. The round logs are pressed against a rotating pulp stone under specified conditions of pressure and temperature.

3.2 Wood Grinding Processes

Grinding can be classified as transversal grinding and longitudinal grinding, depending on the way of putting the wood logs into the grinder magazine. The transversal grinding is also called traditional grinding, which is the wood logs are loaded in the magazine or pocket of the grinder transversally (perpendicularly) to the rotational direction of the stone. And the longitudinal grinding is that the wood logs are loaded parallel to the rotational direction of the stone. And the groundwood processes are divided to GW (Groundwood), TGW (Thermal groundwood), PGW (Pressure groundwood), PGW-S (Super pressure groundwood) according to grinding chamber pressure and spray water temperature. The principle of each process are illustrated in Fig.10 below:

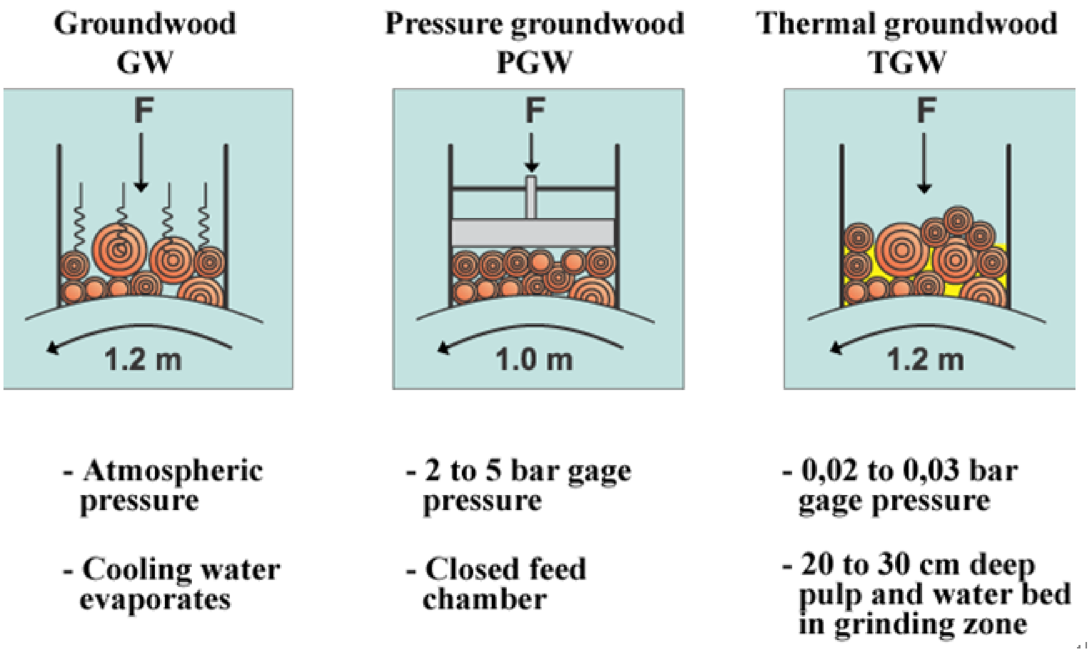


Fig.10: The principle of grinding procedures (Know pap 10.0)

3.2.1 Atmospheric Groundwood (SGW) Processes

Atmospheric groundwood is produced by grinding short billets of softwood against a roughened stone with atmospheric pressure and 70℃-75℃ shower water. The hottest shower water already begins to impair pulp strength and brightness to increase dissolved soilds and to make the SGW mill atmosphere steamy and uncomfortable. In SGW process, the groundwood is conducted through the groundwood channel to coarse screening, then the white water is pumped into shower pipes through a pressure screen which has a basket with holes of the diameter 0.8mm to remove any disturbing shives or fibres, and, further, to thickening. The filtrate from the thickening is returned to the previous process phases. The flow of each shower pipe is measured and adjusted individually. Shower pipe flows are also used as a grinder interlocking to prevent and burn on the grindstones. (Paper Engineers` Association 2009.)

3.2.2 Pressure Groundwood (PGW) Processes

If the wood is ground in a pressurized sealed grinder the pulp is classified as "pressure groundwood" (PGW) pulp. In pressure groundwood processes, the wood is fed into the grinder through a pressurized front chamber. The pressure in the grinding space and front chamber is affected by means of compressed air so that the water boiling point temperature increases. PGW grinding takes place under overpressure (max. 3 bar) depending on the selected grinder construction, whereby also the grinder shower water temperature is typically adjusted in the range of 70℃-120℃ by selecting different grinding process concepts. In each case, to ensure high brightness and strength, the grinding temperature is adjusted to be well below the boiling point of water at the set grinder pressure. So there will not be steam inside the pressurized grinder. (Metso paper.)

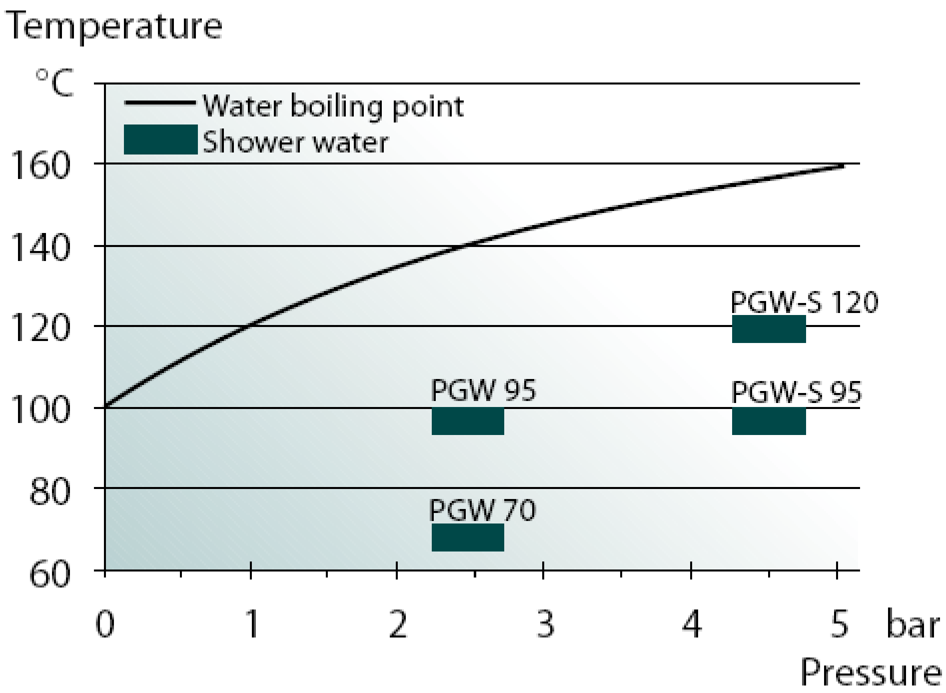


Fig. 11: PGW grinding conditions (Metso paper)

The Figure 11 shows a typical heat balance for a PGW95 grinder. The balance refers to a low-freeness pit pulp at an average motor power of 5.5MW and a grinder output of 100t/d. In grinding, the motor power is converted almost totally into heat and under normal grinding conditions the pit pulp temperature is approximately 20℃ higher than the shower water temperature.

Due to the elevated temperature on the grinding surface and in the wood itself, the wood lignin softens in PGW processes more than in the conventional atmospheric grinding. So, PGW fibers are more easily separated and fibrillation is enhanced. And PGW processes produce mechanical pulp for the highest quality wood-containing products at low energy consumption and environmental load. They are also the best possible choice in terms of process flexibility. (Casey, 1984)

3.3 Grinder

A wood grinder is composed of a cylindrical rotating stone and equipment for pressing the logs against the stone. The stone surface is cooled and the shower water is used for removing fibers away from the grinding zone. The grinders used in Finland are mainly non-pressurized and pressurized grinders by Metso and chain grinders by Voith. (Know pap 10.0) However, many different types of grinders are used around the world. Different wood grinders with different design of feed chamber and feed equipment differ from each other. And pocket grinder, chain grinder and pressure grinder are most usually used in the paper and pulp industries.

3.3.1 Double-Pocket Grinder

The pocket grinders are the first designs of industrial grinders. And the double-pocket grinders have two grinding pockets arranged on opposite sides of the stone which are widely used in Scandinavia and America. The design with opposite pockets results in a very stable construction which withstands high stresses without damage. The magazine above the pocket can hold just one pocket filled with logs. And the filling of one of the pockets is pressed towards the pulp stone and ground hydraulically and the other can be filled for the next batch. (Sixta 2006, page 1090.)

The logs fall down into the grinding chamber, the pusher shoe begins to press the logs against the stone. The pusher shoes are actuated with high pressure water hydraulics (max. 50 bar) or low pressure water hydraulics (approx. 15 bar). The stone is cooled with water, which is supplied to the grinder by four spray pipes. The spray pipes are arranged before and after each pocket. Between the pockets there is a scraper, or doctor, which removes fiber from the stone surface, to prevent the fiber from entering the next pocket and be reground. The rakes are adjusted with minimum clearance to the stone. If the stone wears down, the rakes must be readjusted, otherwise the amount of splinters in the groundwood produced will increase quickly. The figure 12 below is the double-pocket grinder. (Paper Engineers` Association 2009, pages123-125)

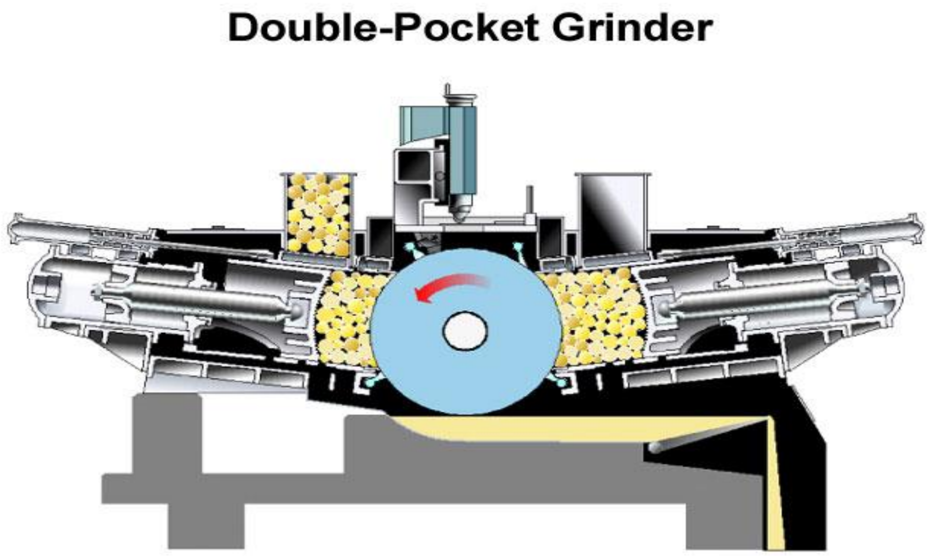


Fig.12: Double-pocket grinder (Know pap 10.0)

3.3.2 Chain Grinder

The chain grinder is widely distributed in Europe. The first large production-size chain grinder using 1m long wood and 1.5m grindstone diameter was installed at the Schongu mill in Germany in 1922. The operation of chain grinder is shown in figure 13. (Honkanen 1993, page 44)

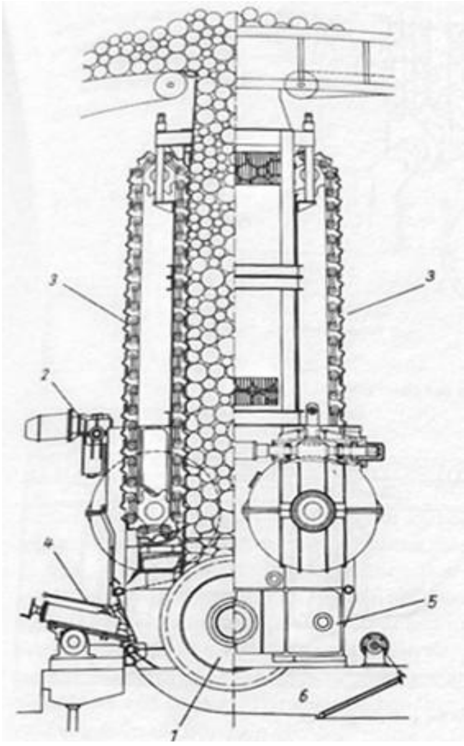


Fig.13: Operating principle of chain grinder (Sixta 2006)

In the figure 13, 1 is pulp stone, 2 is feeding drive, 3 is feeding chains, 4 is stone sharpening equipment, 5 is shower water pipe and 6 is grinding pit. The single long wood magazine, centred over the grindstone with two endless chains moving downward for pressing the logs against the rotating stone, is characteristic for a chain grinder. The chain speed is controlled automatically to maintain a pre-set motor load, production rate or specific energy consumption. The grinder motor ratings used range between 750 and 2500 kW. The pulpstone rim speed may be selected between 18 and 40 m/s. The log length is from 1.0 to 1.5 m, and the grinding zone length is about 1.2 m. The feed chains are operated either electrically or hydraulically, with a feed velocity which is normally 30 to 50 mm/min. Although the constant pressure operation is preferred from a technological aspect, the chain grinder operation can be controlled either by constant feed or by constant load. (Paper Engineers` Association 2009,Page 136)

3.3.3 Pressure Grinder

Groundwood production has been carried out under atmospheric pressure as indicated by Keller with its invention. Further investigations into temperature relationships in grinding have led to the introduction of higher pressures in grinding process. The PGW grinder is designed similar to the atmospheric two-pocket grinder, though the total internal space of the grinder is now pressurized. There are a number of structural differences owing to the raised pressure, though the main structures are similar. (Sixta 2006,page 1095) The figure 14 shows the PGW grinder.

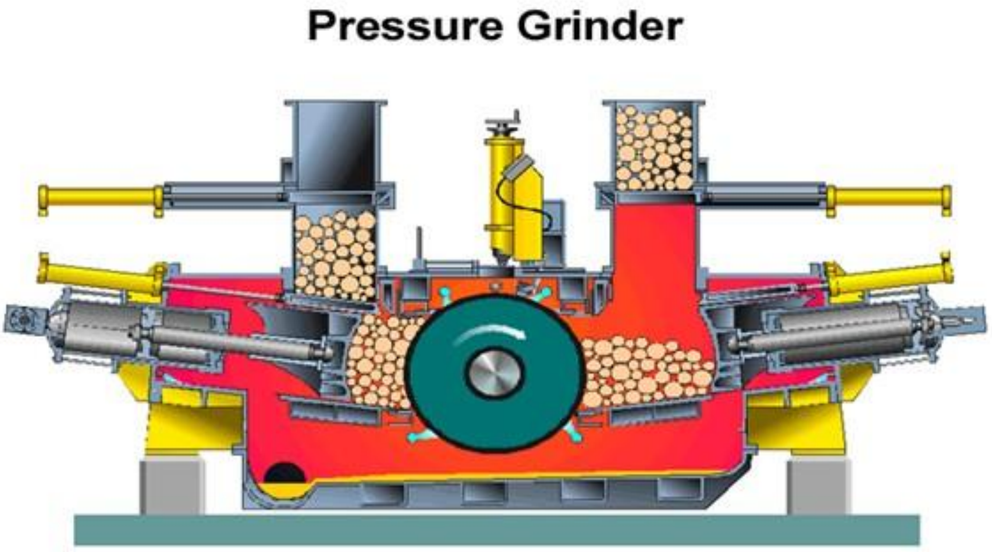


Fig.14: The pressure grinder (Know pap 10.0)

Pulp stone showering and the water hydraulic system are similar to those of the atmospheric grinder. Due to the higher temperature, cooling of water and a separate water-filtering loop is also included. The grinder body is fabricated of welded steel, whose interior is lined with stainless steel and the cast components are also stainless steel. Another gate and a pressure equalizing chamber have been added to feed the logs into the pressurized zone. Two-sided mechanical seals are used for the grinder shaft to minimize the use of fresh water in the PGW and to prevent the colder seal water from bleeding onto the ceramic pulp stones. The shaft seals are mechanical, the gates are sealed, and the machine is equipped with a pneumatic control system operated with compressed air. (Aario et al.1979)

4 WOOD RAW MATERIAL

The wood raw material is an essential part in the production of mechanical pulps and it is greatly affected by temperature, moisture and the time under load. Wood is a highly heterogeneous material with large natural variations in fiber and chemical properties between various wood species and within a specific species. And the chemical composition of the wood will directly affect the pulp properties, especially brightness and the stability of the process through possible pitch problems. For mechanical pulping, the wood quality is especially important. And the requirements of fiber wood are higher for grinding than for refining. The most important requirements of fiber wood are shown in table 1 below. (Paper Engineers` Association 2009)

Wood quality	Healthy, possibly grown straight, less knotty and free from rot.
Wood moisture	As high as possible, should be over 35% in order to exceed the fiber saturation point.
Wood diameter	In grinding, 10-20cm. In refining, 7-10cm.
Debarking state	-Bark is removed completely. -Bark is removed from some retention of phloem. -Wood is completely or partly surrounded by bark.
Resin content	A low resin content is advantage in mechanical pulping.
Wood species	Spruce serves the purpose for mechanical pulping especially in grinding, poplar and aspen also. In refining, both softwood and hardwood species can be processed.

Table 1, The most important requirements of fiber wood in the mechanical pulping (Sixta 2006, page 1075)

The above Table 1 describes the main requirements of six parts of the wood materials, wood quality, wood moisture, wood diameter, debarking state, resin content and wood species in mechanical pulping.

4.1 Introduction of Norway Spruces

Norway Spruce (Picea abies) is one of the most important coniferous species on the European Continent. It is also commonly referred to as the European Spruce and Mountain Spruce. The species and a number of varieties are commonly planted in North America, but are not native there. And some of them are planted in southeastern Canada and northeastern United States. Norway

Spruce makes an excellent timber tree and is used for reforestation extensively in many areas. It is widely used for construction, pulp, furniture, musical instruments and so on. In the past, Norway Spruce was used extensively for the Christmas tree industry as they grew fast; and with a little shearing and the dark green color they looked like the perfect Christmas tree. (Nix.)

Fig.15: the different parts of Norway spruce (needles, flower, fruit, twig, bark.) (Karsten)

Norway Spruce has a lot of identification features. Norway Spruce is a large evergreen coniferous tree growing to 35–55 m (115-180 ft) tall and with a trunk diameter of up to 1-1.5 m. (Conifer Specialist Group.) It is easy to identify by its dark green needles, drooping branchlets and a triangular shape crown. It has dark green needles pointing forward along the twigs, making this species of spruce easier to grasp with the hand. With age increasing, the pendulous, dense branchlets in the upper canopy of mature trees hang straight down for several feet, that are called skirts. The mature tree remains broadly pyramidal, and may either remain branched to the ground or be limbed up. The leaves are needle-like, 12–24 mm long, quadrangular in cross-section (not flattened), and dark green on all four sides with inconspicuous stomatal lines. The twig-like projection (sterigmata), which at the base of each needle remains after the needle, is lost. (Karsten 2010.) Norway Spruce is monoecious, with male flowers scattered throughout the canopy serving as a source of pollen for the female flowers, which give rise to perfectly-shaped, purplish-green then brown cones up to seven inches long. The scaly mature bark of Norway spruce is gray to brown, and is often speckled with dried white resin that drips from bark blisters and pruned limbs. (Ohio Trees.)

Norway Spruce prefers moist but well-drained, acidic soils that may be organic, sandy, or loamy. They can grow 2-3+ feet per year their first 25 years under those good conditions. Otherwise, they may average 1 foot per year in heavy or poor soils. However, it is perhaps the most adaptable common evergreen tree to harsh conditions, including poor, clay, rocky, dry soils of acidic, neutral, or alkaline pH. It thrives under seasonal drought once it is established, and takes well to city pollution. Its only requirement is to not be sited in wet soils, where it will quickly die. It grows in full sun to partial sun in zones 3 to 7. (Gymnosperm Database) On a perfect weather year, and no competition from grass or weeds, the trees could gain over 6 ft of growth in one year. This spruce if given sufficient room to grow will easily grow to over 100 feet tall and be 40 feet wide with spreading branches at the base and will live over 100 years. (Norway spruce.)

4.2 Structure and Chemical Composition of Norway Spruce

At the first stage of longitudinal growth of Norway spruce, the apical and primary meristem form the pith that is mainly composed of parenchyma cells and the cells of primary xylem and phloem. At the secondary stage of growth, the secondary meristem (vascular cambium), xylem and phloem are formed around the pith. And the cells of the vascular cambium differentiate into the cells of the xylem (inside) and the phloem (outside). The tracheid, which has thick lignified cell walls are the main part of the secondary xylem. It also contains a few longitudinal resin ducts and horizontal uniseriate rays and multiseriate rays with resin ducts. (Fagerstedt 2004.) The tracheid cell wall is divided into a thin primary cell wall and a thick secondary cell wall, which consists of three layers (S1, S2, S3), the S2 layer being the thickest (Boerjan et al. 2003). The secondary phloem is composed of sieve cells, parenchyma cells and sclereids and transports the photosynthesis products throughout the tree. At the third stage of growth, the epidermis surrounding the stem is replaced by periderm or bark. (Schweingruber et al. 2006.)

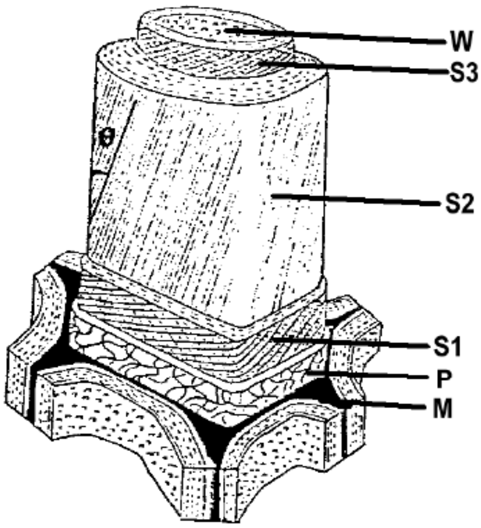


Fig. 16: Sketch showing the composition of a wood fibre (Sundholm 1999)

Figure 16 shows the composition of a wood fibre. The tracheids are bonded together in the wood by a lignin-rich matrix termed the middle lamellae (M). Inside the middle lamellae we find the primary wall (P) and the secondary wall (S). The secondary wall is divided into three layers (S1, S2, S3).

Norway spruce has apparent annual ring boundaries. The annual rings are divided into wide, light earlywood and narrow, dense latewood zones. (Schweingruber et al. 2006) Juvenile wood is the first annual rings around the pith which are formed by the young cambium. Juvenile wood changes to mature wood over several years. The annual rings of juvenile wood with the low latewood percentage are wide. (Saranpää 2003.) Sapwood is the outer layer of the stem and heartwood is formed in the inner part of the stem during ageing. The pits is aspirated in dead heartwood, and its content of phenolic compounds and lignin is higher than in sapwood. (Magel 2000.) All the cells are dead but sapwood contains living parenchyma and epithelial cells in heartwood. While the canal resin is formed by the living epithelial cells, the living parenchyma cells store among triglycerides, starch. (Back 2000.) Compression wood is formed on the lower side of branches and horizontally leaning stems, which has a high lignin content, wood density and compression strength. (Timell 1986.)

Cellulose, hemicelluloses and lignin are the main chemical composition of Norway Spruce. The cellulose microfibrils are irregularly oriented in the primary wall and regularly oriented in the secondary wall. Lignin is situated in inter-fibrillar cavities of cellulose. The thin middle lamella between the cells consists of pectin and lignin. (Fagerstedt 2004.) Mature wood tracheids are larger and have thicker walls and smaller cellulose microfibril angle than juvenile wood tracheids (Saranpää 2003). The lignified cell walls are thought to give mechanical support to the tissues and the phenolic compounds are known to prevent fungal growth (Schweingruber et al. 2006). Norway spruce also contains small amounts of resin (Tjoelker et al., page 335).

Region	Mineral sub-stances	Extract			Cellu-lose Kürschner-Hoffer	Pento-sans	Lignin
		Water	alcohol	ether			
				[%]			
Karelia (2)	0.20	4.1	–	3.1	45.2	9.5	29.0
Petersburg (2)	0.26	1.4	–	1.5	59.1*	10.0	28.1
Germany (1)	0.77	–	1.5	0.7	57.8	11.3	28.3
Romania (3)	0.19	1.7	1.2**	–	51.1	7.3	28.7

Table 2. Chemical composition of Norway Spruce of different geographic regions (Tjoelker et al., page 334)

The table 2 is shown Norway Spruce from different geographic regions with different component of chemical compression. The large geographic distribution of Norway Spruce has led to many investigations that have aimed to determine geographic and genetic differences in the wood chemical composition of the species.

4.2.1 Cellulose

Cellulose is a linear polysaccharide polymer with many glucose monosaccharide units (Cellulose). Cellulose is the most common organic compound on Earth. About 33% of all plant matter is cellulose (the cellulose content of cotton is 90% and that of wood is 40–50%). (Encyclopædia Britannica 2008). Cellulose is a long chain of linked sugar molecules that gives wood its remarkable strength. It is the main component of plant cell walls, and the basic building block for many textiles and for paper. Cellulose is a major component of wood. Cellulose fibers in wood are bound in lignin, a complex polymer. Paper-making involves treating wood pulp with alkalis or bisulfites to disintegrate the lignin, and then pressing the pulp to change the cellulose fibers together. (What is cellulose.)

Cellulose is a linear polymer of β-(14)-D-glucopyranose units in $^{4}C_{1}$ conformation. The fully equatorial conformation of β-linked glucopyranose residues stabilizes the chair structure, minimizing its flexibility (for example, relative to the slightly more flexible α-linked glucopyranose residues in amylose). Cellulose preparations may contain trace amounts (~0.3%) of arabinoxylans. The cellulose chain bristles with polar -OH groups. These groups form many hydrogen bonds with OH groups on adjacent chains, bundling the chains together. The chains also pack regularly in places to form hard, stable crystalline regions that give the bundled chains even more stability and strength. (Updegraff 1969)

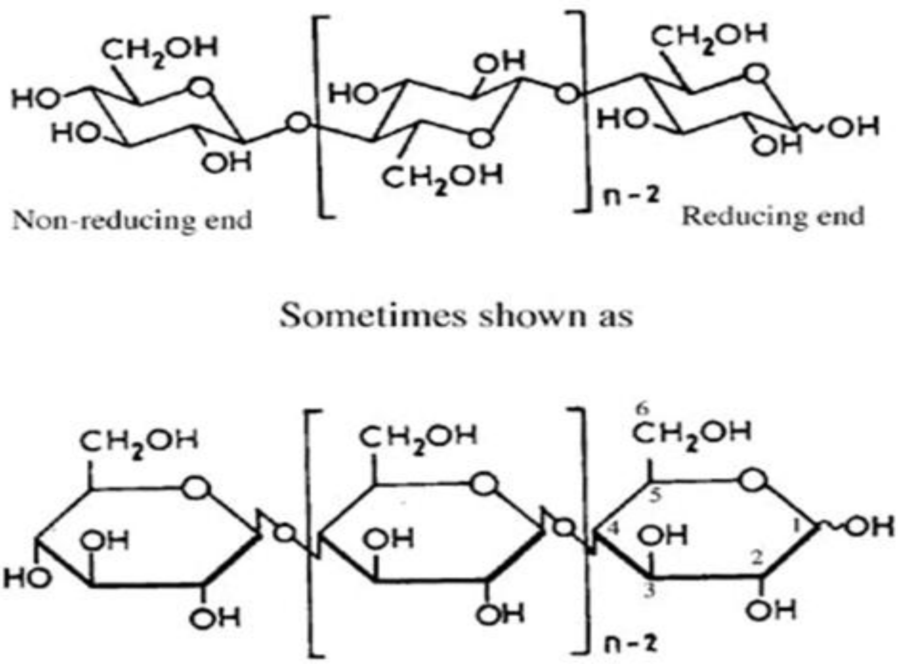


Fig. 17: The Structure of Cellulose (Brown 2007)

4.2.2 Hemicelluloses

Hemicelluloses are any of several polysaccharides, intermediate in complexity between sugar and cellulose, that hydrolyze to monosaccharides more readily than cellulose, which are found in plant cell walls and produced commercially from corn grain hulls (Encyclopædia Britannica 2011).

Hemicellulose contains many different sugar monomers. In contrast, cellulose contains only anhydrous glucose. For instance, besides glucose, sugar monomers in hemicellulose can include xylose, mannose, galactose, rhamnose, and arabinose. Hemicelluloses contain most of the D-pentose sugars, and occasionally small amounts of L-sugars as well. Xylose is always the sugar monomer present in the largest amount, but mannuronic acid and galacturonic acid also tend to be present. (Sjöström 1993.)

Unlike cellulose, hemicellulose (also a polysaccharide) consists of shorter chains. In addition, hemicellulose is a branched polymer, while cellulose is unbranched.

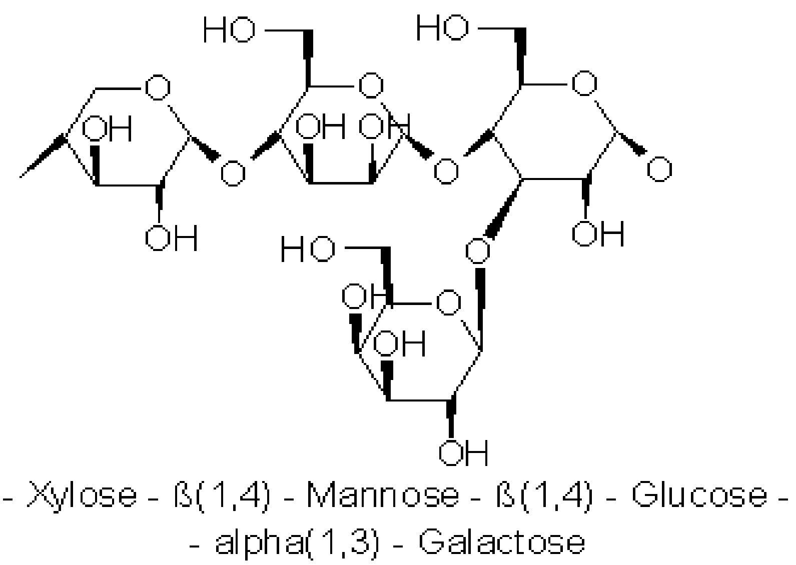


Fig. 18: The Structure of Hemicellulose (Fengel &Wegener 1989)

4.2.3 Lignin

Lignin is a complex polymer, the chief noncarbohydrate constituent of wood, that binds to cellulose fibers and hardens and strengthens the cell walls of plants.

Lignin comprises 18–30% by weight of the dry wood, most of it concentrated in the compound middle lamella and the layered cell wall. (Lebo et al. 2001)

There are three monolignol monomers, methoxylated to various degrees:

p-coumaryl alcohol, coniferyl alcohol, and sinapyl alcohol. Softwood (gymnosperm) lignin (Picture 4) is composed mainly of guaiacyl units, hardwood (angiosperm) lignin of guaiacyl and syringyl units and grass lignin of p-hydroxyphenyl, guaiacyl and syringyl units.

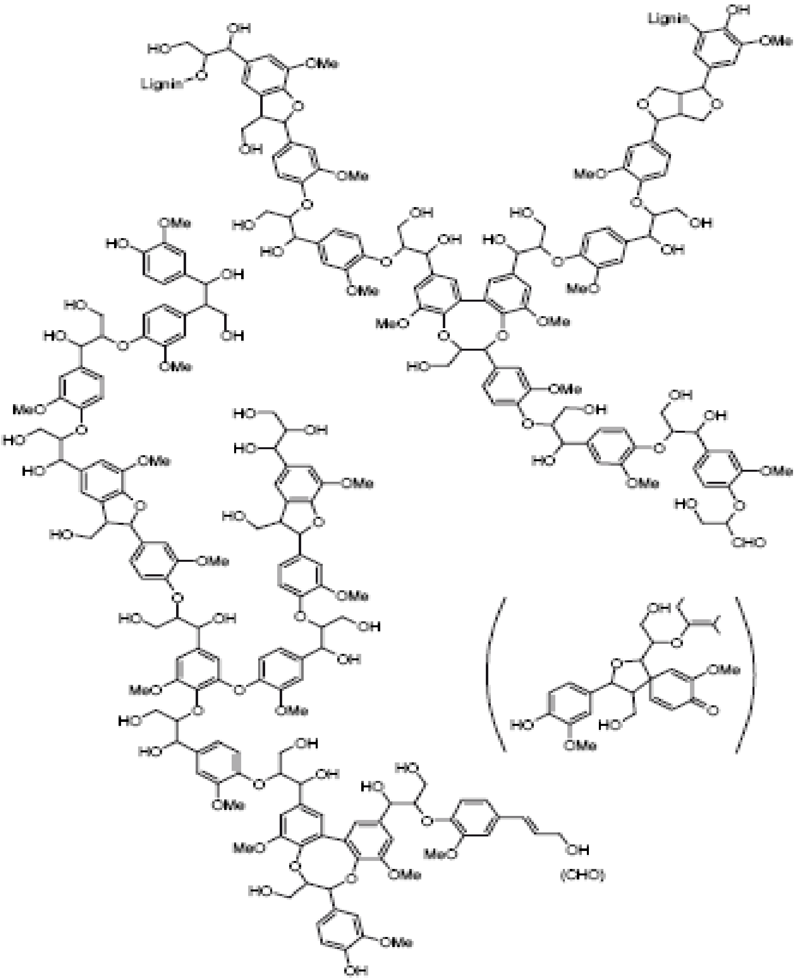


Fig.19: Structural scheme for softwood lignin (Brunow et al. 1998)

Coniferyl alcohol is the major component of gymnosperm lignin, whereas lignin in broad-leaved trees is composed of both coniferyl and sinapyl alcohol. p-hydroxyphenyl units are abundant e.g. in compression wood lignin and grass lignins (Freudenberg & Nash 1968). All lignins contain small amounts of incomplete or modified monolignols, and other monomers are prominent in non-woody plants. In Norway Spruce, the proportion of the guaiacyl units is 98% and *p*-hydroxyphenyl units only 2%. (Ralph 2001.)

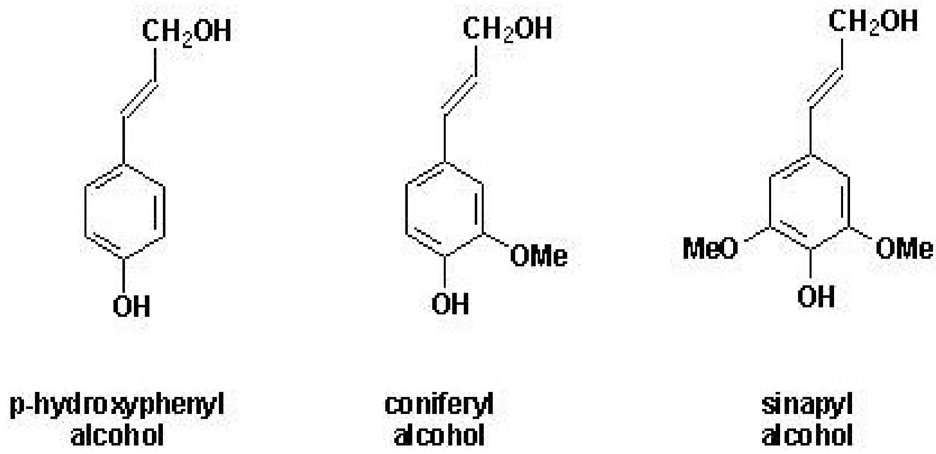


Fig. 20: Chemical structure of the main components of lignin (Freudenberg & Nash 1968)

Highly lignified wood is durable and therefore a good raw material for many applications. It is also an excellent fuel, since lignin yields more energy when burned than cellulose. Mechanical, or high-yield pulp used to make newsprint contains most of the lignin originally present in the wood. This lignin is responsible for newsprint's yellowing with age. Lignin must be removed from the pulp before high-quality bleached paper can be manufactured from it. (Sjöström 1993.)

4.2.4 Extractives and Ash

Extractives are the compounds which wood contains except the major structural components. These compounds can be extracted from wood with organic solvents (terpenes, fats, phenols and waxes) or hot water (tannins and inorganic salts). The amount of extractives in wood varies from 5 to 20% by weight and includes a wide variety of organic chemicals. Many of these function as intermediates in tree metabolism as energy reserves or participate in the tree’s defense mechanism against microbiological attack. The extractives contribute to wood properties such as color, odor, and decay resistance. (Wood.)

Ash is the inorganic residue remaining after ignition at a high temperature.The ash content is 0.2–0.5% by weight for temperate woods and 0.5–2.0% by weight for tropical woods. The principal elemental components of wood ash are calcium and potassium with lesser amounts of magnesium, sodium, manganese and iron. Carbonate, phosphate, silicate, oxalate, and sulfate are likely anions. (Forest Products Laboratory 1984.)

4.3 Application of Norway Spruce

The Norway Spruce is one of the most widely used plants, both in and outside of its native range. The main uses of Norway Spruce are problems with the respiratory system as the material of medicine, because the essential oils of the spruce desinfect and clean the lung. It is used in forestry for timber and paper production, and as an ornamental tree in parks and gardens. (Tjoelker et al., page 340) It is also widely planted for use as a Christmas tree. The young shoots of Norway spruce can be used for brewing spruce beer and also as spruce tea. The wood has also been used for violin sound boards, but is not the preferred choice. Norway Spruce cone scales are used as food by the caterpillars of the tortrix moth. (United States Forest Service.)

5 EXPERIMENTAL PARTS

5.1 Experimental Design and Methods Used

The atmosphere grinding process was used to pulp the Norway spruce pulps in laboratory scale. Two different pulps were made, one pulp used traditional grinding way, another one used longitudinal grinding way. In the traditional grinding process, the angle 0° Norway spruce pieces whose every side length was not more than 4.8cm were grinded. And four different angles (0°,15°,30°,45°) Norway spruce pieces were ground in longitudinal grinding way. Before grinding, the Norway spruce wood chips were cooked in the pot for 10 minutes, then put into the grinder. After grinding, shives were separated by screening with 0.2mm slots, and all pulps were collected and filtrated by using pressure filter, then further work was proceeded. Finally, the pulps were divided into two different parts which in total include 6 different pulps. The experimental device parameters are shown in the table 3.

Pulps	Pulp characteristics
Traditional grinding pulp	Grinding angle : 0°
Longitudinal grinding pulp	Grinding angle : 0°, 15°, 30°, 45°.

Table 3: The experimental design parameters

From the table 3 above, it can be seen clearly that there were two different grinding pulps in this experiment, and the features of each pulp. However, in the grinding process, not only the grinding way can affect the characteristics of the pulp, but also the grinding angle, the spray water temperature, pressure and so on.

5.2 Raw Material

Norway spruce as raw materials came from the Saimaa University of Applied Sciences´ laboratory. The fresh wood was measured and marked in different angles and cut along the mark by the electric saw. Then, the cutting machine was used to cut 15 pieces of each angle of wood. The every side length of the wood pieces was not more than 4.8cm. The wood pieces were stored in the refrigerator at temperature 5℃ for maintaining their moisture content. Before grinding, wood pieces were cooked for 10 minutes. The purpose of wood cooking is to increase the wood temperature. After this step, the wood pieces were put into the gate of the grinder in the right way.

5.3 Grinding Method and Conditions

The atmospheric grinder was used in this process (see fig. 20). The main body of the grinder is made of strong and corrosion resistant cast iron. The grinding zones are 8cm length and grindstones have 30cm diameter. And the 1500rpm motor with 18kw power has been installed and connected to an inverter for the desired grindstone speed. The wood pieces were dropped into the pockets through the feeding gates on the top of the grinders and switch was pressed to start pushing the wood pieces against the rotating grindstone. There are two shower water nozzles to clean and cool the grindstone and the temperature of the shower water is 56-57°C. With atmospheric pressure of 100kPa (1bar) and maximum 100°C boiling temperature of water, 15 pieces of spruce of each angle were prepared and cut so that the side length is less than 4.8cm. And they were separated to put into hot water to be cooked for 10 minutes. After cooking, the wood blocks were taken from the boiler. Before grinding, the power switch of the grinder, the water valve and the hydraulic pump switch were opened and also the switch which controls the motor, then water went into the grinder and the grinder machine was warmed for about 5 minutes. Then the wood blocks were put in the grinder for grinding. The inside grinding stone of the grinder was rolling in the counterclockwise direction. In the traditional grinding method, the angle of the wood blocks is 0°. The wood was put into the grinder so that the horizontal line of the wood block is in the upside. And in the longitudinal grinding method, the wood blocks include angles 0°, 15°, 30°, 45°. The angle could be seen from the line which is slanting to the right and intersects with the wood´s bottom side. The opposite side of the angle side has an opposite wood line. And the angle side was put on the right side. In grinding in the right way, the wood blocks were pressed sideways against a rotating grinding stone so that the wood fibers are perpendicular to the motion of the pulpstone surface. The rotating stone transferred through grit particles on the stone and gave energy to the wood. Finally, the wood fibers are separated and after few minutes, the pulp including some slivers is discharged through a hole whose diameter is 1cm to the bucket and.

Fig. 21: The atmospheric grinder in laboratory

5.4 Screening

As the pulp leaving the grinder contains undefibered material like slivers, shives, fiber bundles up to 5 %, it was necessary to use the mechanical treatment to separate pulp. The slot screening was used in the laboratory to separate bundles from the pulp. The pulp was screened in Somerville screen with 0.2mm diameter slots. When screening, water was added to the screen for easy and high efficiency. After slot screening, the accept pulps were collected in the buckets and the shives and any heavier particles were removed. After that the accept pulp was taken out to the pressurized filter and the pulp cakes were made.

5.5 Pressure Filtering

The pressure filter was used for collecting all fibers and fines. The screened pulp was put into the filter tank and water was put into the pump tank after connecting the filter with the vent valve. The cover was opened by foot pressing and covered with the filter cloth, then it was closed. In filtering process, the compressed air is used and the diameter of the filter disc is about 45cm. At last, water being discharged from the process were purified. After all the pulp had gone to the filter stock, the filter valve was closed, and was repressed by the pressure sector until it had no water outside. And the cover was opened and the cake was gotten. When the cake had been removed, the filter cloth was washed with oscillating water showers and a new filtration cycle began. The pulp cakes were stored in the buckets and kept inside the refrigerator at 5 ºC.

5.6 Pulp Properties Test

The drainability of a pulp suspension in water in terms of the “Canadian Standard” freeness (CSF) number, water retention value (WRV), fiber length and coarseness (FS-300) were tested for each group, the test results are listed in following tables.

5.7 Paper Sheet Making

The “Rapid-Köthen” sheet former was used to make the laboratory paper sheets. The basic weight of the paper sheets were 80g/m^2, ten paper sheets which were within ±3% range of 80g/m ^{2} were made by recycled water. 3-5 papers were tried to make and the dry weights were compared and pulp volume was found closed to the standard values until getting the dry paper weight was about 2.5g per sheet.

5.8 Paper Sheet Test

Some basic properties, optical properties and strength properties were measured from the sheets. The following properties were measured from the sheets.

- Grammage
- Thickness, density and bulk
- Air permeability
- Tensile strength
- Tearing strength
- Bursting strength
- Brightness
- Opacity

6 RESULTS AND DISCUSSION

The different pulps were compared based on the different grinding methods and grinding angles. The main aim was to find out the differences of pulp and paper properties between the traditional grinding and longitudinal grinding and the regular pattern of pulps and paper properties of different angles. All results received from the experiments are illustrated in the charts below.

Comparison Between “Canadian Standard” Freeness Measurements

The International Standard specifies a method for determination of the drainability of a pulp suspension in water in terms of the “Canadian Standard” freeness number. It was also called CSF-number, the measurement principle of CSF number is same as SR. During measuring CSF-number, whilst stirring, transfered 1000ml±5ml of homogeneous pulp suspension which was made by 3g dry weight pulp to a clean measuring cylinder. Then the bottom of the chamber of the freeness tester was closed and the top lid and the air-cock were opened. The sample was mixed by closing the top of the cylinder with the hand and the cylinder was inverted 180° by three times and tried to avoid air get into the stock at this stage. The stock was poured as rapidly as possible into the chamber and the stock should be motionless in the chamber in the end. The top lid and the air-cock were closed and the bottom lid was opened. Then the air-cock was opened to start the flow after 5s. The CSF-number was read from the scale of the graduated glass when the water had stopped to flow from the side orifice. And the pulp cake was took out from the screen plate and filtered by filter paper. After filtering, the cakes were dried in the oven and the weights were measured. Finally, the values were compared with the table and values were got which were close to the standard values. In this pulp test, the consistency of pulp was 3g/l, the test was performed following the procedures strictly stated on ISO 5267/2-1980(E). All the test values are shown in the following table 4.

Classification of pulp (°)	Freeness number (ml)
Reference	157
0	160
15	75
30	71
45	60

Table 4: CSF-number of each pulp group.

Based on table 4, the chart 1 was made as follow:

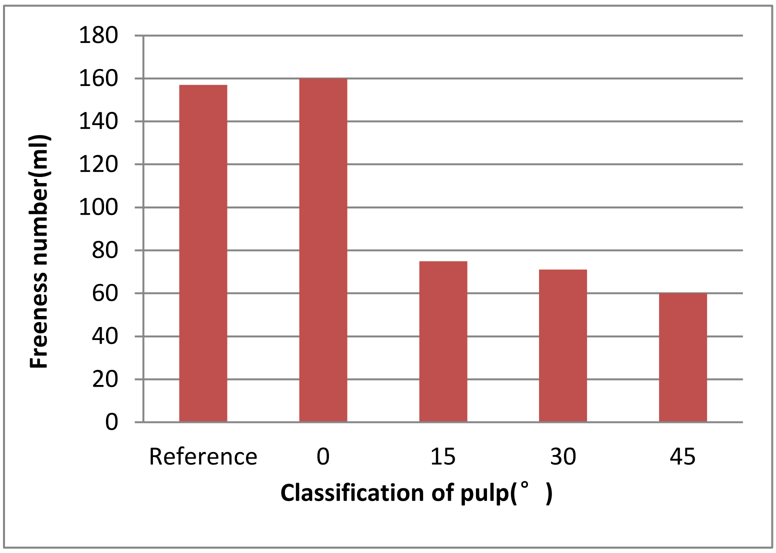


Chart 1 : CSF-number versus the categories of the pulp

In the chart 1, it can be found that the CSF-number of reference grinding pulp was nearly the same with longitudinal grinding angle 0° pulp. And for the longitudinal grinding pulp, the freeness number was decreasing as the angle was increasing. And the angle 15 °and 30° had the similar CSF-number which was from 75ml to 71ml.

Fiber Length

“Kajaani FS 300” is a fiber length analyzer which is used for measuring the fiber length and coarseness. It gives fiber length distribution, the average fiber length and the fiber coarseness of a sample. 0.2 g dry weight fibers were taken from each pulp sample, and then they were diluted in 5l of water, after that 50 ml sample was taken out from the 5l pulp twice. An analyzer measures and adjusts the fibre contents after receiving a sample. The system diagnostics check the operation of the measurement instrument before the actual analysis. Finally, the results of average length weighted fiber length and coarseness of each pulp are shown below:

Classification of pulp (°)	Length weighted fiber length (mm)
Reference	0.40
0	0.61
15	0.38
30	0.32
45	0.23

Table 5: Length weighted fiber length measured in Kajaani FS 300.

Based on table 5, the chart 2 was made as follow:

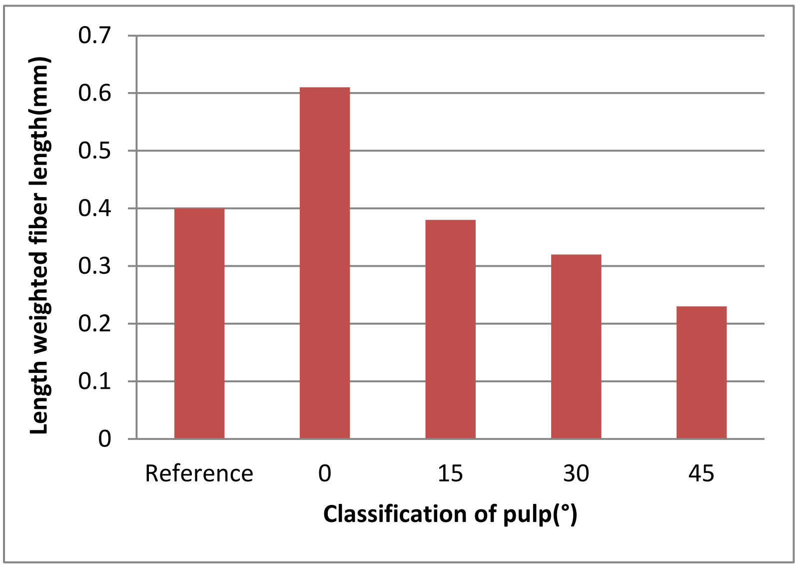


Chart 2 : Length weighted fiber length versus the categories of the pulp.

According to the chart 2, it can be seen that fiber length decreased with the increasing the angle of the longitudinal grinding pulp, the reason was fiber breakage while grinding. However, the fiber length decreased slowly from angle 15° to angle 45°, and the longest fiber length was angle 0 of longitudinal grinding pulp. For the traditional grinding pulp, it was nearly similar with the angle 15° pulp and just 0.02mm difference.

Classification of pulp (°)	Coarseness (mg/m)
Reference	0.437
0	0.476
15	0.488
30	0.406
45	0.339

Table 6 : Coarseness values measured in Kajaani FS 300.

Based on table 6, the chart 3 was made as follow:

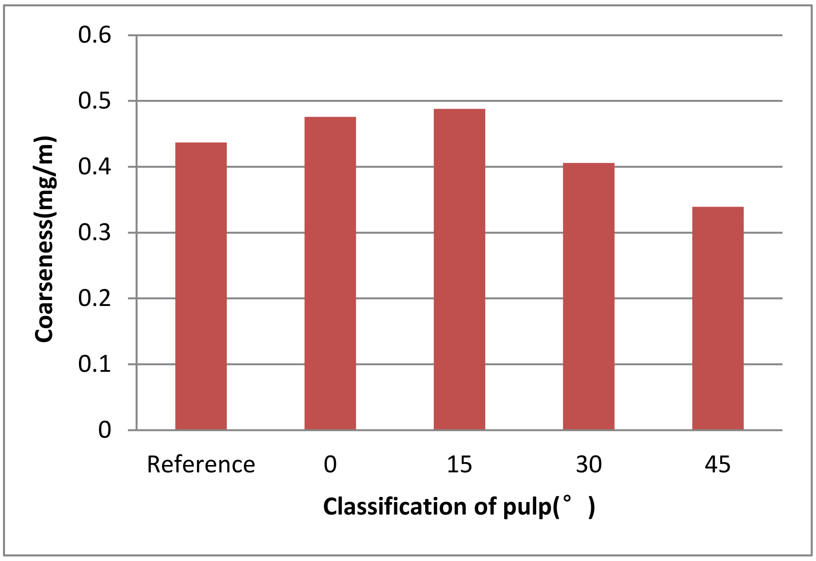


Chart 3: Coarseness values versus the categories of the pulp.

In the chart 3, the coarseness value decreased with increasing the angle of the longitudinal grinding pulp, the most coarse pulp is the angle 15° pulp and it is nearly similar with the angle 0° pulp . Connecting with chart 2, it can be seen that obviously the longer the fiber length, the more coarseness the pulp. For the traditional grinding pulp, the coarseness value was nearly similar to the angle 30° pulp and just 0.031mg/m difference.

Water Retention

The water retention value (WRV) is an important parameter in the manufacture of pulp and paper. It is an indication of the ability of a sample of wood fibre or pulp mass to retain water. The WRV-value increased with increasing grinding angle, the reason is that the grinding angle increases, the fiber length decreases and it was easier for the fiber to retain more water. The four pieces 1g dry weight pulp were weighed for each group. The test pad consisting of pulp fibers is carried out by placing a pad of moist fibers in a centrifuge tube that has a fritted glass filter which at its base and formed by dewatering a pulp suspension on a wire screen. The test pad is centrifuged under a specified centrifugal force for 10 minutes, weighed, dried and reweighed. The WRV value equals the ratio of the water mass to the dry mass. The method used to determine the WRV has been standardized and is described in the international standard ISO 23714:2007. And water retention values are shown in the following table 7:

Classification of pulp (°)	Water retention value(%)
Reference	182%
0	151%
15	187%
30	196%
45	220%

Table 7: The water retention values of each pulp group

Based on table 7, the chart 4 was made as follow:

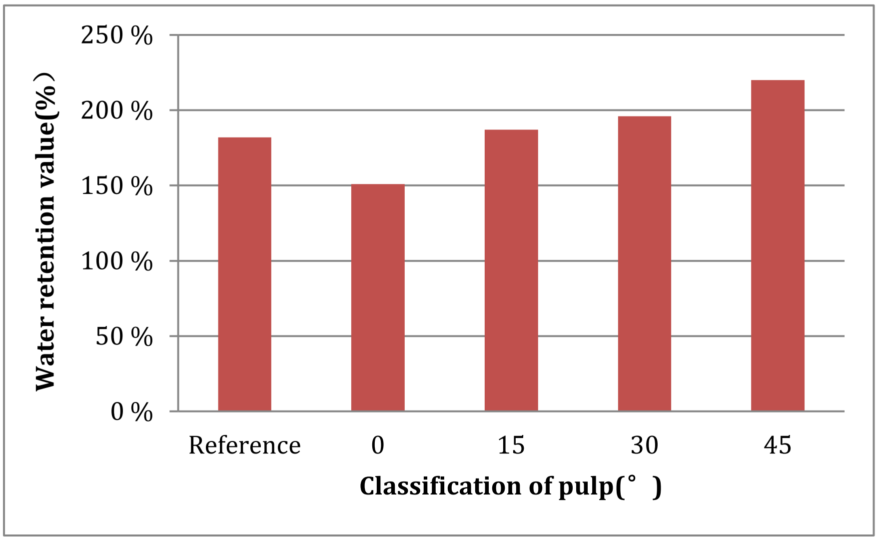


Chart 4: Water retention value versus the categories of the pulp

Apparent from the graph was that with the angle increasing except the reference one, the water retention value increased from 151% to 220%. It means that the big grinding angle can improve the water retention value. Connecting with the chart 1, the angle 0° pulp which had the biggest CSF freeness number had the worst water retention ability. As the degree of refining, the bigger the CSF freeness number, the smaller the water retention value. And the water retention value of reference grinding pulp was similar with the angle 15° pulp.

Grammage, Thickness, Density and Bulk

Grammage is the weight of the one square meter of paper or board (g/m^2). Grammage of the sheet is measured from the trimmed sheet (area of the trimmed sheet is $0.02m^2$). The normal expression for thickness of paper is μm. The thickness was measured by using a pile of six trimmed sheets using a motor driven micrometer. The sheets should not move during the measurement. The density of the paper is the mass per unit volume calculated as the ratio between basis weight and thickness of the material in kg/m^3. The bulk is the inverse number of the density expressed as cm^3/g. As the bulk decreases, the density increases, so that the paper sheets will become more smoothness, glossier, less opaque, darker and have lower strength. The “L&W Micrometer 51” was used to five sheets` thickness measurement. And the final results which were measured are showed in table 8.

Classification of pulp (°)	Bulk value (cm^3/g)	Basis weight/sheet (g/m^2)	Average Thickness (mm)	Density (kg/m^3)
Reference	2.26	82.0	0.185	443
0	2.22	86.0	0.191	450
15	1.97	83.4	0.165	507
30	1.90	85.0	0.162	525
45	1.79	84.8	0.152	558

Table 8: The basic properties of each group pulp.

Based on table 8, the chart 5 was made as follow:

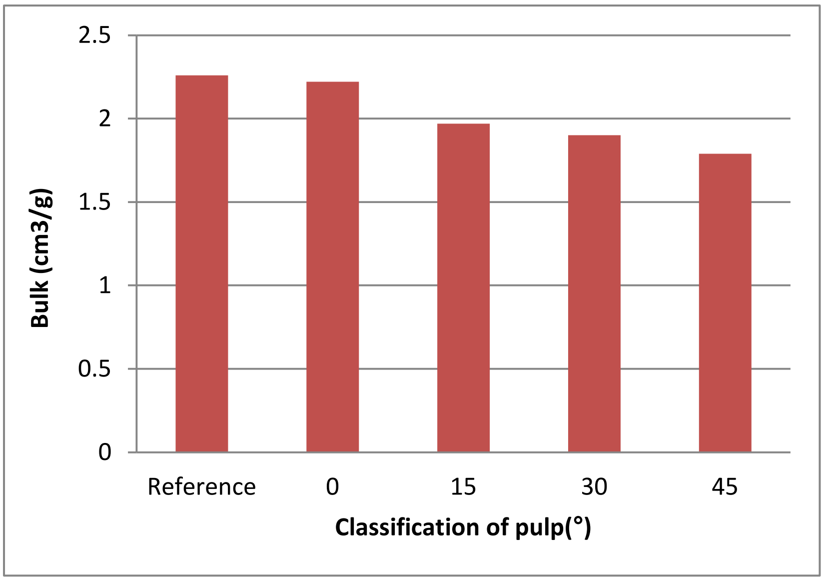


Chart 5: Bulk value versus the categories of the pulp.

In the chart 5, it can be seen that the bulk value is decreasing from reference one to the angle 45°. And the biggest bulk value was the angle 0 ° longitudinal pulp. In the longitudinal grinding method, the bulk values went down significantly with the grinding angle increasing. Comparing the traditional grinding method with the longitudinal grinding method, the reference pulp was nearly equal to the angle 0 ° longitudinal pulp.

Tensile Strength

Tensile strength of the paper is the maximum force per unit width that a paper strip can resist before breaking when applying the load in a direction parallel to the length of the strip. However, the extent of interfiber bonding is considered the most important factor contributing to tensile strength properties. In the experiment, a vertical tensile testing machine was used to measure tensile strength and its unit is KN/m. The number of the measurements is 10 while testing paper sheets. The width of the test sample was 15mm and the length was 18-20 cm, and the drawing speed is 100mm/min. A piece is attached to the device from both ends and the arrow is pressed upwards. When the piece was broken and the device stopped. Tensile index is equal to dividing tensile strength by the basis weight of the sheet and the width 0.015m. The unit is Nm/g. The method used to determine the tensile strength has been standardized and is described in the international standard ISO 1924-1:1992(E). The values of the tensile index are shown in the following table 9.

Classification of pulp (°)	Tensile index (Nm/g)
Reference	18.3
0	21.4
15	23.6
30	24.1
45	27.4

Table 9: Tensile index values of each pulp group.

Based on table 9, the chart 6 was made as follow:

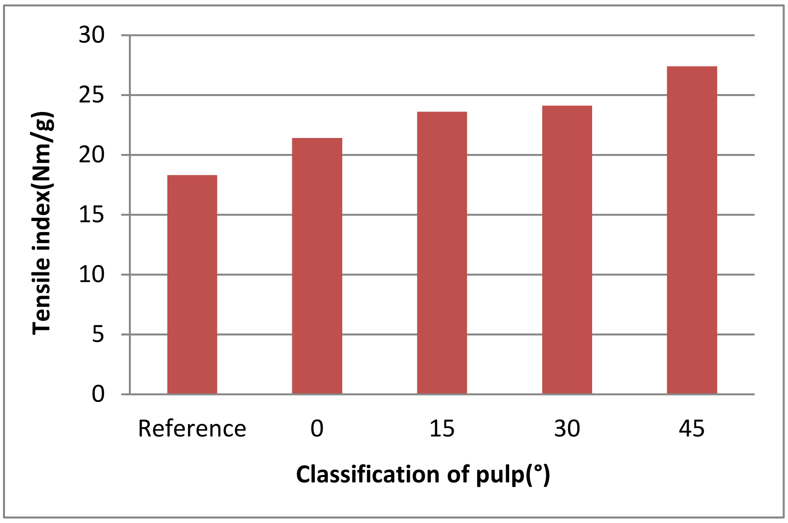


Chart 6: Tensile strength versus the categories of the pulp.

As we can see from the chart 6, the tensile strength increased with the angle increasing. And the tensile strength of the angle 15° pulp was similar to the angle 30° pulp. Comparing the traditional grinding pulp with the longitudinal grinding pulp, the reference pulp had the lowest tensile strength and the angle 45° pulp had the highest tensile strength. That means the bigger the grinding angle, the higher the tensile strength.

Tear Strength

The tear strength is the force perpendicular to the plane of the paper sheet required to tear multiple plies through a specified distance after the tear has been started. An Elmendorf-type tearing tester is used and the result is quoted in mN. The Elmendorf-type tester is a pendulum that applies the force and measures a loss in the potential energy of the pendulum equating to the work done in tearing the paper. Tear strength simulates the situation when there is some defect in the edge of the paper web, e.g. hole, tear or stick. And the tear strength was affected by fiber length, degree of bonding between fibers and degree of orientation of fibers in paper at least. 12 test pieces (62mm long and 50 mm wide) were cut for the measurement and tested one by one. And the tear index was provided by dividing the tear strength by the basis weight (mN m2/g). The international standard ISO 1974:1990(E) is used to determine the tear strength. The average values of the tensile index are shown in table 10.

Classification of pulp (°)	Tear index (mNm^2/g)
Reference	1.01
0	1.61
15	1.16
30	1.04
45	0.81

Table 10: Tear strength values of each pulp group.

Based on table 10, the chart 7 was made as follow:

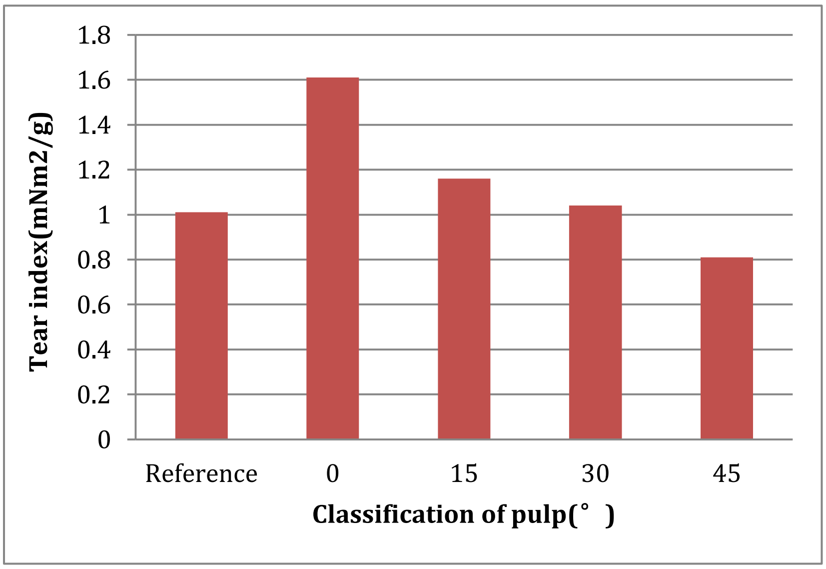


Chart 7: Tear strength versus the categories of the pulp.

According to the chart 7, the tear strength of the longitudinal grinding pulp was decreasing with the angle were increasing. And the value of tear strength of the reference pulp with the angle 30° pulp was nearly the same. And the value of the angle 0° grinding pulp was significantly higher than other pulps´.

Burst Strength

Bursting strength is the maximum uniformly distributed pressure which is applied at right angles to its surface that a single sheet of paper can withstand under the test conditions. The unit for bursting strength is kPa. Dividing bursting strength by the basis weight of the sheet provides the bursting index(kPa m^2/g). Higher bursting strength means greater shredding energy. It is a rapid and easy test to perform and does not require test pieces cut exactly. Five measurements were taken from each sample to give the average value of burst strength. ISO 2758:1983(E) is used for determination of bursting strength. The values of burst index are shown in table 11.

Classification of pulp (°)	Burst index (kPa m^2/g)
Reference	0.70
0	0.92
15	0.96
30	1.04
45	1.08

Table 11: Burst strength values of each pulp group.

Based on table 11, the chart 8 was made as follow:

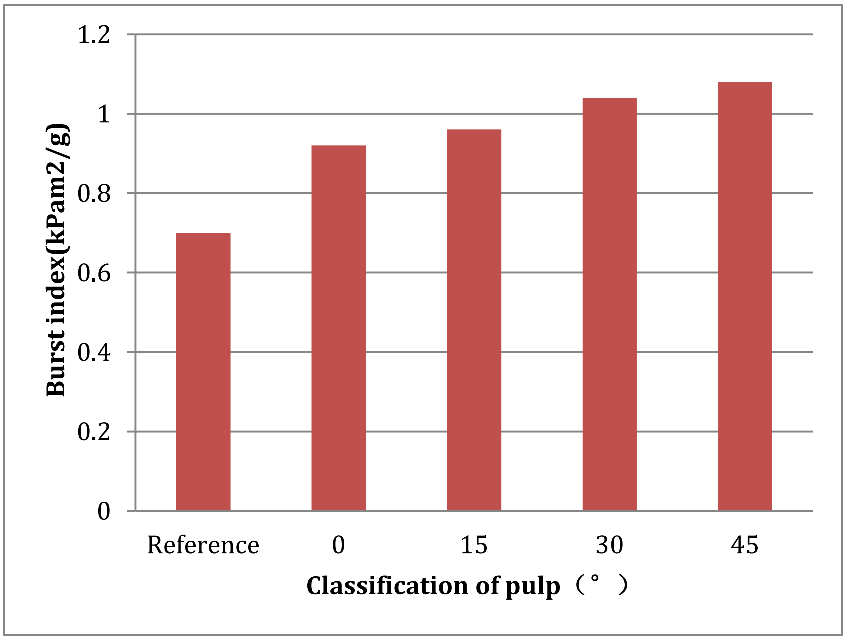


Chart 8: Burst strength versus number of revolution.

From the chart 8, we can see that the grinding angle increased, burst strength increased in both pulps. And the pulp made by reference grinding had a lower burst strength than the pulp made by longitudinal grinding. However, the difference between the longitudinal grinding pulp was around 4%. That means the burst strength of each longitudinal grinding pulp is almost the same even when there is a big difference in grinding angle.

Air Permeability

The air permeance of paper is normally measured using air leakage instruments of different types. These instruments measure in one way or another the flow of air through a defined area of the paper caused by a defined difference in pressure between the different sides of the paper sample. The air permeance measured using Bendtsen tester is the volume flow of the air that pressure difference (0.74kPa) provides through a $10cm^2$ area. And the international standard ISO 5636-3:1992 is used to determinate the air permeability. The values of air permeability are given in table 12.

Classification of pulp (°)	Air permeability (ml/min)
Reference	233
0	261
15	190
30	128
45	80

Table 12: Air permeability of each pulp group

Based on table 12, the chart 9 was made as follow:

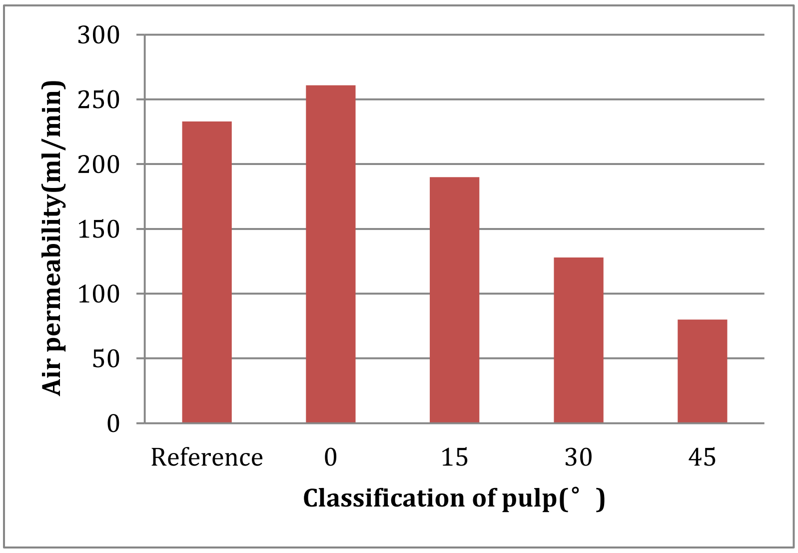


Chart 9: Air permeability versus the categories of the pulp.

As the chart 9, it can be seen clearly the air permeability was decreasing except in the reference pulp. The higher air permeability, the more porosity. In the longitudinal grinding method, the grinding angle increased, the density increased, the air permeability of these pulp decreased clearly. Comparing the traditional pulp with the longitudinal pulps, the reference pulp had higher air permeability than the angle 15°, 30°, 45° pulps.

Optical Properties

The opacity of paper measures how opaque it is. The higher the opacity the more opaque paper is. The opacity portrays the paper's ability to prevent the print from the other side of the paper from shining through. The opacity is calculated as 100 times the ratio of the reflectance factor of a single sheet over a black background to the reflectivity. The brightness is measured as reflectivity with a combination of an incandescent lamp and an R_{457} function. The brightness values of the pulps going into the paper provide an excellent measure of the maximum whiteness that can be achieved with proper tinting. “Lorentzen & Wettre – Elrepho” was used to measure optical properties and ISO 2470 -1977(E) is for determination of the brightness, and the method ISO 2471 - 1977(E) is for determination of the opacity. The values of brightness are shown in the following table 13:

Classification of pulp (°)	Brightness value (%)
Reference	60.99
0	61.89
15	62.36
30	62.98
45	62.61

Table 13: Brightness values of each pulp group

Based on table 13, the chart 10 was made as follow:

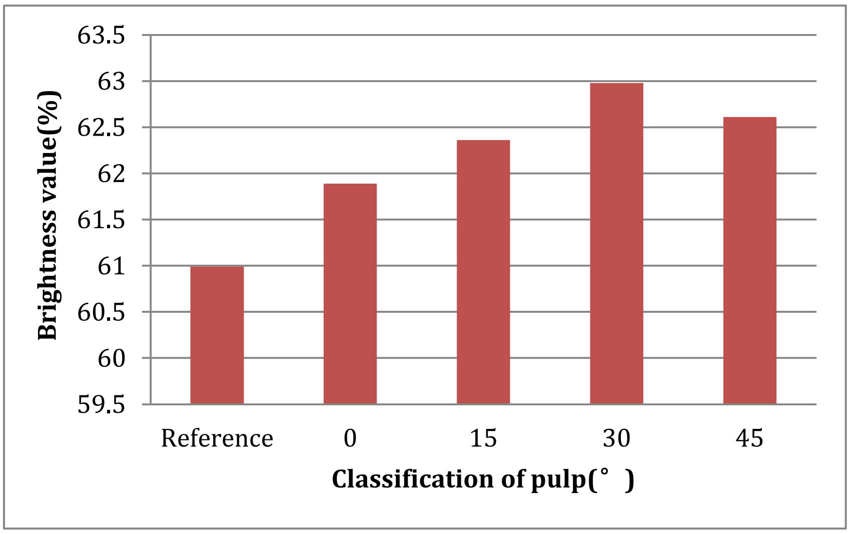


Chart 10: Brightness value versus the categories of the pulp.

From the chart 10 can be seen that the brightness value increased from the reference pulp to the angle 30° pulp, while it decreased in the angle 45° pulp. Between the traditional grinding and longitudinal grinding, the reference pulp had the lowest brightness and the angle 30° had the highest brightness. That means the grinding angle has a big effect on the paper's brightness.

7 SUMMARIES

Two different pulps which were made by traditional grinding method and another longitudinal grinding method were measured in this laboratory experiment. The wood blocks were prepared for each group and ground in the laboratory scale with a pressure grinder separately after 10 minutes cooking. And some amount of the grinding pulps were taken to screen to separate detrimental impurities from good pulp with minimum good fiber losses and moderate costs. After screening, these pulps were pressed to make cakes by the air pressurize filter. This step was for reducing the pulp lose. As a result, there were five different Norway spruce pulps were made. One kind of pulp was ground by traditional grinding way with angle 0° and called reference pulp. Other four pulps were ground by longitudinal grinding with angle 0°, 15°, 30°, 45°. After pulp making, the CSF freeness number, water retention and fiber length were measured. And 50 pieces paper were made for paper testing and their dry weight were all around 2.5g. Finally, thickness, strength properties, air permeability, brightness and opacity were measured in the laboratory.

This experiment confirms that the traditional grinding and longitudinal grinding have a big difference and the different grinding angles also have effects on the pulp and paper properties. As the results obtained below, there are some relationships between these properties and they can affect each other. In the fiber length and coarseness measurement, the figures show that the bigger the grinding angle, the shorter the fiber length, the less the coarseness. And in water retention measurement, the short fibers have a big retention value and that means the short fibers have better ability of retaining water than the long fibers. In the opposite way, the CSF freeness number is decreasing as the water retention value is increasing. Combining these pulp properties, it can be seen clearly that the fiber length is one of the factors which can affect the pulp freeness and water retention.

Within the basic properties of the paper sheets, the basis weight and density of the reference pulp is the smallest in these pulps. Sheet density directly influences strength and opacity. When thickness measurements are related to grammage, the ratio of these two parameters will give a value for apparent sheet bulk, so the bulk is mainly correlating with thickness. As the results show, the bulk is decreasing from the reference pulp to the angle 45° pulp. And the air decreased permeance is affecting by sheet consolidation, which means low amount of air or longer time is needed to pass through a shorter fiber composed handsheet. In the strength properties, the tensile strength is almost increasing, but the tear strength is decreasing, and the burst strength is increasing with the grinding angle increasing. As the results show, the tensile strength is mostly dependent on the degree of bonding between the fibers. And the tearing strength of paper is generally dependent on the fiber length over most of its refining range. The fiber strength, bonding degree between fibers and the fiber orientation in the sheet, also influence the tear strength. And papers made of long fibers have higher tear strength properties than paper made of short fibers. For the opacity properties measurement between these pulps, it almost increasing, groundwood fibers with a high proportion of fines produce high opacity papers as do short fibred pulps.

Generally, as the grinding angle increases, the water retention value , the tensile strength, the burst strength and brightness value increase gradually. However, the pulp`s CSF freeness number, fiber length and coarseness, and the paper`s tear strength, bulk and air permeability decrease gradually. In fact, between the traditional grinding and longitudinal grinding, the longitudinal grinding with small angle gives better effects on paper making. And the grinding process can bring visible diversifications to pulp and paper properties.

Figure

Table

Chart

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APPENDIX

List of standards used at work

Determination of drainability of pulp by Canadian Standard freeness method - ISO5267/2 - 1980(E)

Determination of fibre length and coarseness - TAPPI single fiber mode

Determination of water retention value (WRV) – ISO 23714:2007(E)

Preparation of laboratory sheets for physical testing -- Part 2: Rapid-Köthen method- ISO 5269-1:1998(E)

Determination of thickness, density and specific volume - ISO 534:2005 (E)

Determination of tearing resistance (Elmendorf method) - ISO 1974:1990(E)

Determination of tensile properties - ISO 1924 - 1:1992(E)

Determination of bursting strength - ISO 2758:1983(E)

Determination of air permeance (medium range) -- Part 3: Bendtsen method - ISO 5636-3:1992

Measurement of diffuse blue reflectance factor (ISO brightness) - ISO 2470 - 1977(E)

Determination of opacity (paper backing) -- Diffuse reflectance method - ISO 2471 - 1977(E)